

CORRELATION OF FLAME DENSITY  
AND KNOCK INTENSITY

42  
A. K. K. K.  
K. K. K.

A THESIS

Presented to  
the Faculty of the Division of Graduate Studies  
Georgia Institute of Technology

In Partial Fulfillment  
of the Requirements for the Degree  
Master of Science in Mechanical Engineering.

by  
George Frederick Epps  
1948

NW 4-23-48

100377

ii

CORRELATION OF FLAME DENSITY  
AND KNOCK INTENSITY

Approved:

*[Handwritten signature]*  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

Date Approved by Chairman 13 September 1948

## ACKNOWLEDGEMENTS

I would like to express my appreciation to Doctor Ray L. Sweigert for suggesting the problem for study, and also for his kind assistance and encouragement, without which the completion of the work would have been much more difficult. Professor Robert L. Allen served as my thesis advisor and his assistance and guidance is greatly appreciated. My sincere gratitude is also extended to Doctor Homer S. Weber, Professor D. W. Coe, Mr. Thomas D. Sangster and Mrs. Charlotte B. Cates for their kind assistance and encouragement.

## TABLE OF CONTENTS

	PAGE
Acknowledgments-----	iii
Introduction-----	1
Historical Survey-----	2
Description of General Test Equipment-----	5
Test Procedure-----	9
Tabulation of Results-----	24
Discussion-----	26
Conclusions-----	29
Bibliography-----	30
Appendix I-----	31
Appendix II-----	39
Appendix III-----	52



## LIST OF TABLES

TABLE	PAGE
I Sample Data Sheet-----	19
II Average Data-----	20
III Tabulation of Results-----	24

## LIST OF FIGURES

FIGURE		PAGE
1	Engine Photograph-----	13
2	Air Metering System Photograph-----	14
3	Indicator Equipment Photograph-----	15
4	Schematic Diagram of Assembly of General Equipment-----	16
5	Schematic Diagram of Assembly of Indicator Equipment-----	17
6.	Schematic Diagram of Air Metering System----	18
7	Oscilloscope Image Photographs of Pressure Variations-----	21
8	Oscilloscope Image Photographs of Pressure Variation-----	22
9	Pressure Variation Curve for Compression and Power Strokes-----	23
10	Correlation Curve of Flame Density Versus Knock Intensity-----	25
11	Orifice for Air Metering System-----	44
12	Schematic Diagram of Assembly of Orifice Plate in Pipe Line-----	45
13	Schematic Diagram of Equipment for Cali- brating Pressure Indicator-----	47
14	Sample Photographs of Oscilloscope Image When Calibrating Pressure Indicator-----	48

## LIST OF FIGURES

FIGURE		PAGE
15	Calibration Curve for Pressure Indicator Equipment-----	49
16	Calibration Curves for Wet and Dry Bulb Thermometers-----	51



## LIST OF ABBREVIATIONS AND SYMBOLS

$a$	is $\frac{P_o}{P_i}$
$A_1$	is the instantaneous area of the combustion flame.
$a'$	is the area of the air orifice in square feet.
$a''$	is the area of the air orifice in square inches.
$\alpha$	is the coefficient of discharge for the orifice.
AEDC.	is after bottom dead center.
BDC.	is bottom dead center.
BTDC.	is before top dead center.
$C$	is the compressibility factor.
$d_1$	is the instantaneous density of the combustion flame.
$F$	is the amount of fuel burned in pounds per minute.
$\phi$	is the connecting rod angle from the cylinder axis in degrees.
$\delta$	is the connecting rod angle to the crank.
$g$	is the acceleration of gravity in feet per second per second.
$(h_A - h_B)$	is the pressure drop across the orifice in inches of alcohol.
$k$	is the ratio of the specific heat of air at constant pressure to that at constant volume.
$L_c$	is the length of the crank in inches.
$L_r$	is the length of the connecting rod in inches.
$m$	is the distance from top dead center to the top of the piston.

- $n_m$  is the ratio of the specific heat of the fuel-air mixture of constant pressure to that at constant volume.
- $n_p$  is the ratio at the specific heat of the products of combustion at constant pressure to that at constant volume.
- $\Delta$  is the angle of the crank from the cylinder axis.
- $P$  is the pressure in pounds per square inch absolute.
- $P_1$  is the initial absolute pressure of the fuel-air mixture.
- $(P_A - P_B)$  is the pressure drop across the air orifice in pounds per square inch.
- $P_o$  is the pressure of the gas in the cylinder after the reaction.
- $P_1$  is the pressure of the burned gases in the cylinder after expansion.
- $P_2$  is the pressure of the unburned gases in the cylinder after expansion.
- $Q$  is the quantity of air flow in pounds per minute.
- $p$  is the quantity of air flow in pounds per second.
- $r$  is the ratio of the pipe area to the orifice area.
- $R$  is the compression ratio.
- $T$  is the temperature in degrees Fahrenheit absolute.
- $T_1$  is the temperature of the burned gases in the cylinder after expansion in degrees Fahrenheit absolute.

- $T_2$  is the temperature of the unburned gases in the cylinder after expansion in degrees Fahrenheit absolute.
- $V$  is the volume in cubic feet.
- $V_A$  is the total volume in the cylinder at bottom dead center, in cubic inches.
- $V_B$  is the clearance volume in the cylinder at top dead center in cubic inches.
- $V_c$  is the piston displacement in cubic inches.
- $V_m$  is the volume caused by displacement  $m$  in cubic inches.
- $V_t$  is the initial volume of the mixture in cubic feet.
- $V_l$  is the volume of the gas in the cylinder after reaction in cubic feet.
- $V_i$  is the volume of the burned gases in the cylinder after expansion, in cubic feet.
- $V_{s1}$  is the instantaneous velocity of the combustion flame in feet per second.
- $(V_t - V_l)$  is the volume of the unburned gases in the cylinder after expansion in cubic feet.
- $v_l$  is the specific volume of the initial gases in the cylinder, in cubic feet per pound.
- $v_2$  is the specific volume of the burned gases in the cylinder in cubic feet per pound.
- $v_i$  is the instantaneous specific volume of the combustion flame in cubic feet per pound.
- $w$  is the density of the upstream air in pounds per cubic foot.



- $w_a$  is the weight of dry air (one pound).
- $w_v$  is the weight of the water vapor in pounds per pound of dry air.
- $w_e$  is the work of expansion of air.
- $w_c$  is the work of compression of air.
- $w_m$  is the weight of fuel-air mixture taken in in pounds per minute.
- $w_{ms}$  is the weight of fuel-air mixture taken in on intake stroke in pounds.
- $\bar{w}_u$  is the weight of unburned gases in the cylinder in pounds.
- $\bar{w}_t$  is the weight of all gases in the cylinder at initial conditions in pounds.
- $\bar{w}_1$  is the weight of the burned gases in the cylinder in pounds.
- $\bar{w}_r$  is the weight-rate of burning of the gases in the cylinder in pounds per second.
- $y$  is the ratio  $\frac{P_1}{P_1}$
- is the ratio  $\frac{1 - n_m}{1 - n_p}$
- $T_o$  is the temperature of the gases in the cylinder after the reaction, in degrees Fahrenheit absolute.
- T.D.C. is top dead center.

## CORRELATION OF FLAME DENSITY AND KNOCK INTENSITY

### INTRODUCTION

#### Purpose:

A satisfactory physical explanation of the phenomenon of detonation (knocking) in internal combustion engines has not yet been presented and the reason for this is probably that the basic fundamentals affecting detonation have not been determined. It is the purpose of this investigation to determine whether or not the density of the flame of combustion shows any correlation with the intensity of knock. If it results that there is some correlation between the two, then a foundation for a sound physical explanation of knocking may result.

#### Objective:

It is the objective of this investigation to obtain sufficient data from the operation of a C.F.R. Engine under different knocking conditions to calculate by thermodynamic relations the density of the combustion flame. With this flame density and the corresponding knock intensities and other data, an analysis will be made of the results and a graph drawn in order to determine if there is a correlation between the density of the combustion flame and the intensity of the knock.

## HISTORICAL SURVEY

The significance of knocking, or detonation in the combustion chamber of an engine has been recognized by many and the detrimental effect of this phenomenon in an engine has been the cause of considerable research in laboratories all over the world.

It was in the year 1881 that detonation may be said to have been discovered, when Berthlot and Vieille announced in the Comptes Rendus their discovery of the rapid acceleration of the initial flame speed in gaseous explosions and the final attainment of the enormously higher velocity of the explosive wave.

Soon after the publication of the work of Berthlot and Vieille, H. B. Dixon took up the study of combustion. Dixon attacked the problem of detonation in a different manner, i.e., by the utilization of photography in studying explosions. His photographic investigations were carried out between 1895- and 1903, and added considerable to the knowledge of detonation.

Several hypotheses have been advanced to explain detonation, but the one which has gathered more support is that which was first advanced by Recardo. This hypothesis, which is called the Autoignition Hypothesis, suggests that detonation might be spontaneous ignition of the unburned part of the charge ahead of the normal flame front. However, the explana-



tion as set forth by Recardo failed to show why kerosene with a higher ignition temperature than carbon disulfide detonated more readily in a given engine. A satisfactory explanation of this apparant contradiction was presented in 1935 by E. S. Taylor<sup>1</sup>. Taylor showed that no contradiction need exist if it is assumed that detonation will occur only when the unburned part of the charge is heated to or above its ignition temperature and held there for a definite length of time. This interval is known as the ignition delay.

Work in Europe led to the publication of another explanation of detonation by Heinz Langweller, called the Hydrodynamic Theory of Detonation. This theory, unfortunately, lacks the extreme simplicity which the Autoignition Hypotheses possesses. Langweller suggests in the Hydrodynamic Theory that the magnitude of the detonation speed is dependent upon what he called microscopic quantities, such as heat content, explosive pressure, etc., whereas the physical state of the individual explosives particularly is unimportant. This he claims is exemplified by the quality of detonation speed of solid and liquid explosives of the same density. Langweller maintains that the reaction process, which in explosions and combustion defines the linear speed of transformation, plays no part at all in the phenomenon of detonation. He concluded that it may therefore be assumed that the

---

<sup>1</sup>Leary, W. A. and Taylor, E. D., The Significance of the Time Concept in Engine Detonation. (N.A.C.A. Wartime Report, W-32, 1943)

explosion before the detonation front is at a stage independent of its physical state and that the radiation of the gases of combustion is sufficient to activate a thin layer of the explosive before the detonation front and there create the high explosive pressure and temperature. Also the magnitude of the detonation speed is given only by the propagation speed of a shock wave in a gas at the explosive pressure and temperature. That this speed of propagation is greater than the normal velocity of sound in this gas, Langweller explained, is a result of the higher amplitude of the shock.

Although the Autoignition Hypothesis and the Hydrodynamic Theory and other explanations have been presented in an effort to bring to light the physical explanation of the phenomenon of detonation, none have been found to be completely satisfactory and the problem remains with but a faint idea to scientists who are still seeking the true answer.

## DESCRIPTION OF GENERAL TEST EQUIPMENT

The assembly of the general equipment used in this test is shown in the schematic diagram on page 16.

## ENGINE:

The engine used was a C.F.R. Knocking-Testing engine connected by belts to a synchronous motor. This engine incorporated a movable cylinder head which permitted the varying of the compression ratio while the engine was in operation. The exact compression ratio was determined from the micrometer reading which indicated the cylinder height. This micrometer was adjusted by the Tilt Method according to the standard procedure given in the C.F.R. Knocking-Testing Manual.

Specifications of the engine are as follows:

Compression ratio scale-----	4 to 10
Bore, inches-----	3.25
Stroke, inches-----	4.50
Displacement, cubic inches-----	37.4

## IGNITION:

The ignition system of the engine consisted of a point-coil arrangement which obtained its current from the synchronous motor and generator used to supply power to the engine control panel. A neon tube indicated the exact spark setting in degrees before and after top dead center.



#### CARBURETION:

The carburation system of the engine consisted of three fuel containers, each of which had a float carburetor and a glass indicator which showed the height of the fuel in the carburetor. A screw which varied the height of the container and its float and float chamber served as a throttle control by varying the fuel head which caused the flow of fuel into the manifold. A three-way valve permitted switching from one container to either of the other two without stopping the engine. The amount of fuel put into the containers was carefully weighed on balanced scales. A manifold heater with a carbon pile reostat insured control of the mixture temperature.

#### AIR METERING SYSTEM:

The system for measuring the amount and determining the condition of the air taken into the engine was constructed and installed according to the method of J. L. Hodgson<sup>2</sup> and consisted of a  $1\frac{1}{2}$  inch nominal diameter pipe with an orifice installed between flanges (see Figure 12). A micromanometer indicated the pressure drop across the orifice. Downstream from the orifice was mounted a 50 gallon surge tank which insured a steady flow of air through the orifice. The temperature of the air entering the intake manifold was controlled by an electric air heater to which was connected a carbon pile reostat. Thermometers were installed as shown in Figure 4.

---

<sup>2</sup>Ower, E., The Measurement of Air Flow, (London, Chapman and Hall, Ltd. 1927) pp. 56-57.

#### KNOCKMETER:

Measurement of the knock intensity in the engine was made by use of a bouncing pin and knockmeter. The bouncing pin assembly consisted of a stainless steel pin inserted in a hollow barrel and resting on a steel diaphragm. The diaphragm was exposed to the combustion gases in the cylinder. A special head assembly containing two leaf springs and a bumper and bumper spring and adjusting screws was attached to the upper end of the barrel. When detonation occurred in the cylinder, the high pressure wave deflected the diaphragm rapidly, causing the pin to bounce upward. The force of the pin bent the bottom point leaf upward until it made contact with the upper point. The harder the knock, the greater the deflection of the diaphragm and the bounce of the pin, and the longer the contact points remained together. The contact of the points closed an electrical circuit containing a hot wire resistor which surrounded a thermocouple unit on the back of the knockmeter. The longer the two points were in contact, the longer was the period of current flow through the hot wire and the higher its temperature became. This increase in generated electromotive force. The thermocouple was connected to a millivoltmeter which is called a knockmeter. The knockmeter reading increased with an increase in knock intensity.

#### SYNCHRONOUS MOTOR:

A synchronous motor which was connected by belts to the C.F.R. Engine was used to start the engine.

#### INDICATOR EQUIPMENT:

The arrangement of equipment for recording the pressure-volume variations in the engine is shown in Figure 5. The indicator equipment consisted of a phase modulator system in which a small change in capacity in the indicator plug was utilized to modulate a radio frequency carrier wave generated by an electron coupled oscillator. The modulated wave was then demodulated, amplified, and applied to the deflecting plates of a cathode-ray oscilloscope for photographic recording. The image projected on the oscilloscope screen was synchronized with the engine rotation by a coil-magnet synchronizer directly connected to the engine shaft and wired to the synchronizing poles of the oscilloscope.

A speed graphic camera, mounted as shown in Figure 4, was utilized to record the image on the oscilloscope screen.

## TEST PROCEDURE

The operating procedure for gathering the data necessary for calculating the flame density and for recording the knock intensity in the engine was as follows:

Before the engine was started the equipment setup (shown in Figure 4) was checked to assure that the engine had the proper amount of oil in the crankcase, the rocker arms were lubricated, the fuel containers were filled, the pin was in place and properly connected, and the micromanometer was set at zero. In addition, initial data such as barometric pressure and fuel density were taken before the engine was cranked.

The engine was started by closing the switch to the synchronous motor which was connected by belts to the engine. As soon as the engine oil pressure as indicated on a pressure gage on the instrument panel, registered above twenty pounds per square inch the ignition switch was closed, immediately followed by the opening of the three-way valve to one of the fuel containers. As soon as the engine began firing, the valve controlling the flow of cooling water to the coolant condenser was opened and adjusted to allow the proper amount of cooling water to flow through.

The engine was allowed to warm up for approximately two hours under non-knocking conditions before starting the test runs. During the warm-up period, the spark advance was



set at twenty degrees before top dead center, a condition which was held constant throughout the entire test.

After the warm-up period the compression ratio and fuel level were adjusted to give a low knock intensity within the combustion chamber. The bouncing pin was then so adjusted that the knockmeter indicated a low knock intensity. (It must be remembered that this knockmeter reading has no absolute value, having meaning only when compared with other readings at the same bouncing pin setting.)

With the knock intensity properly adjusted the engine was allowed to run several minutes before beginning a test run. This period was necessary in order to allow the instruments to come to equilibrium and in order to make certain that the knockmeter did not vary exceedingly.

With all conditions at equilibrium the test run was begun by turning the three-way valve to allow the fuel in one of the other two containers to flow into the engine. In this container was four-hundred milliliters of fuel and the time required for the engine to burn this four-hundred milliliters of fuel was determined by use of a stop-watch. Collection of the following data was made every five minutes during the burning of the fuel:

1. Wet bulb temperature
2. Dry bulb temperature
3. Knockmeter reading
4. Oil pressure

5. Oil temperature
6. Panel-generator D. C. Volts
7. Manifold heater A. C. amps
8. Air heater A. C. amps
9. Fuel level in carburetor
10. Air temperature after heater
11. Fuel-air mixture temperature
12. Coolant temperature
13. Spark setting
14. Cylinder height micrometer setting
15. Bouncing pin setting
16. Revolutions per minute
17. Pressure drop across the air orifice
18. Air temperature before the surge tank

As the last of the four-hundred milliliters of fuel was burned the time was recorded and the engine was stopped by opening the ignition and synchronous motor switches. Immediately after the engine stopped the bouncing pin was replaced by the condenser type pressure indicator plug and as soon as the indicator leads were connected to the oscillator detector and cooling water was flowing through the indicator, the engine was again started and allowed to operate until the same conditions which prevailed during the burning of the four-hundred milliliters of fuel were reached. As soon as these conditions were again in equilibrium the oscillator



detector and cathode ray oscilloscope were turned on and adjusted to project a clear image of the pressure variations within the combustion chamber of the engine on the oscilloscope screen. The camera mounted in front of the oscilloscope was then focused and the lighting adjusted so as to record both the image and the metric scale which was mounted on the face of the oscilloscope screen. With the camera properly adjusted, four pictures were taken of the image and the numbers of the pictures recorded on the data sheet.

With the taking of the pictures of the image the test run was ended and as soon as the pressure indicator was replaced by the bouncing pin, another run was begun. Succeeding test runs were conducted in the same manner but at different knock intensities, these knock intensities being controlled by varying both the fuel level and the compression ratio.

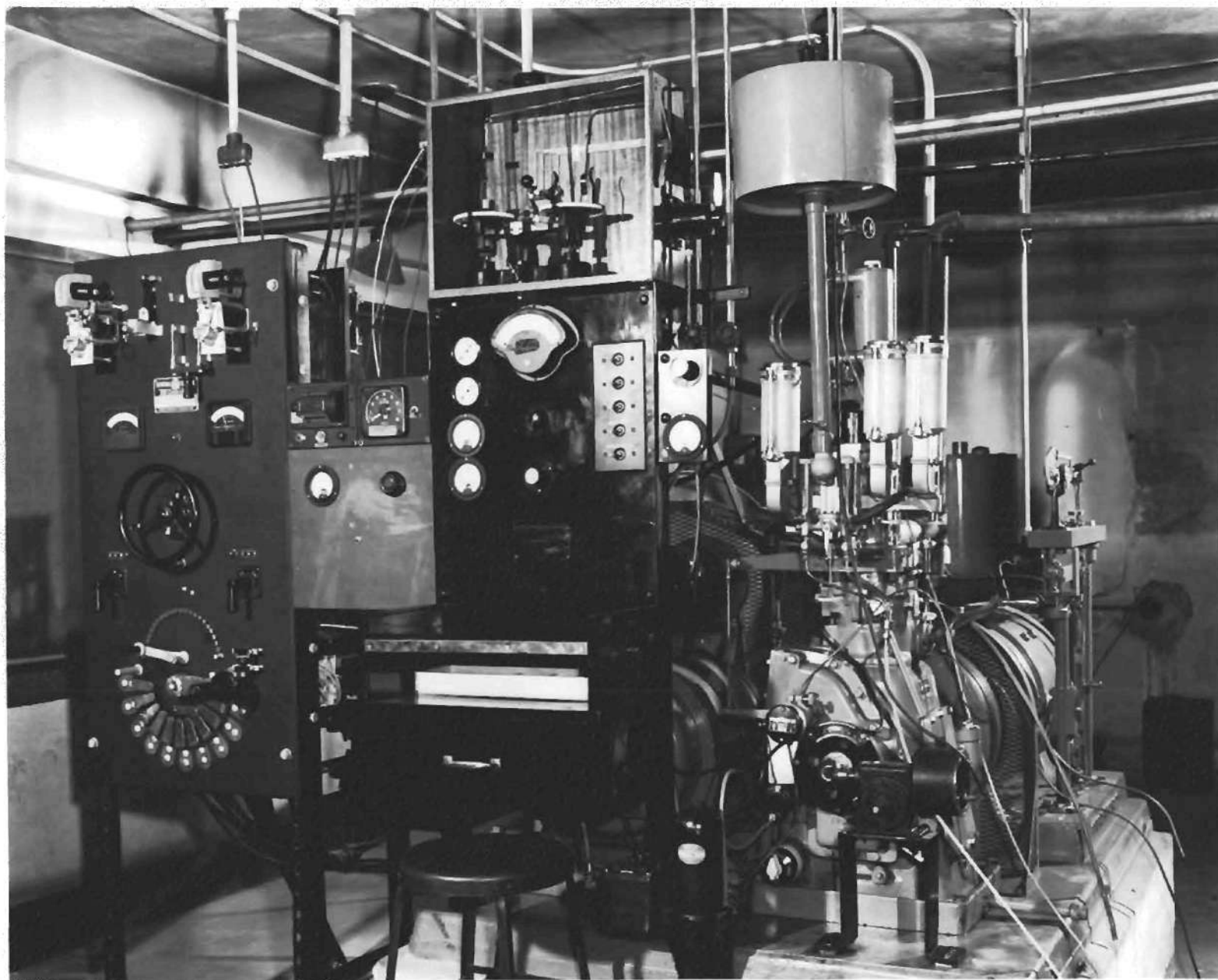


FIGURE 1

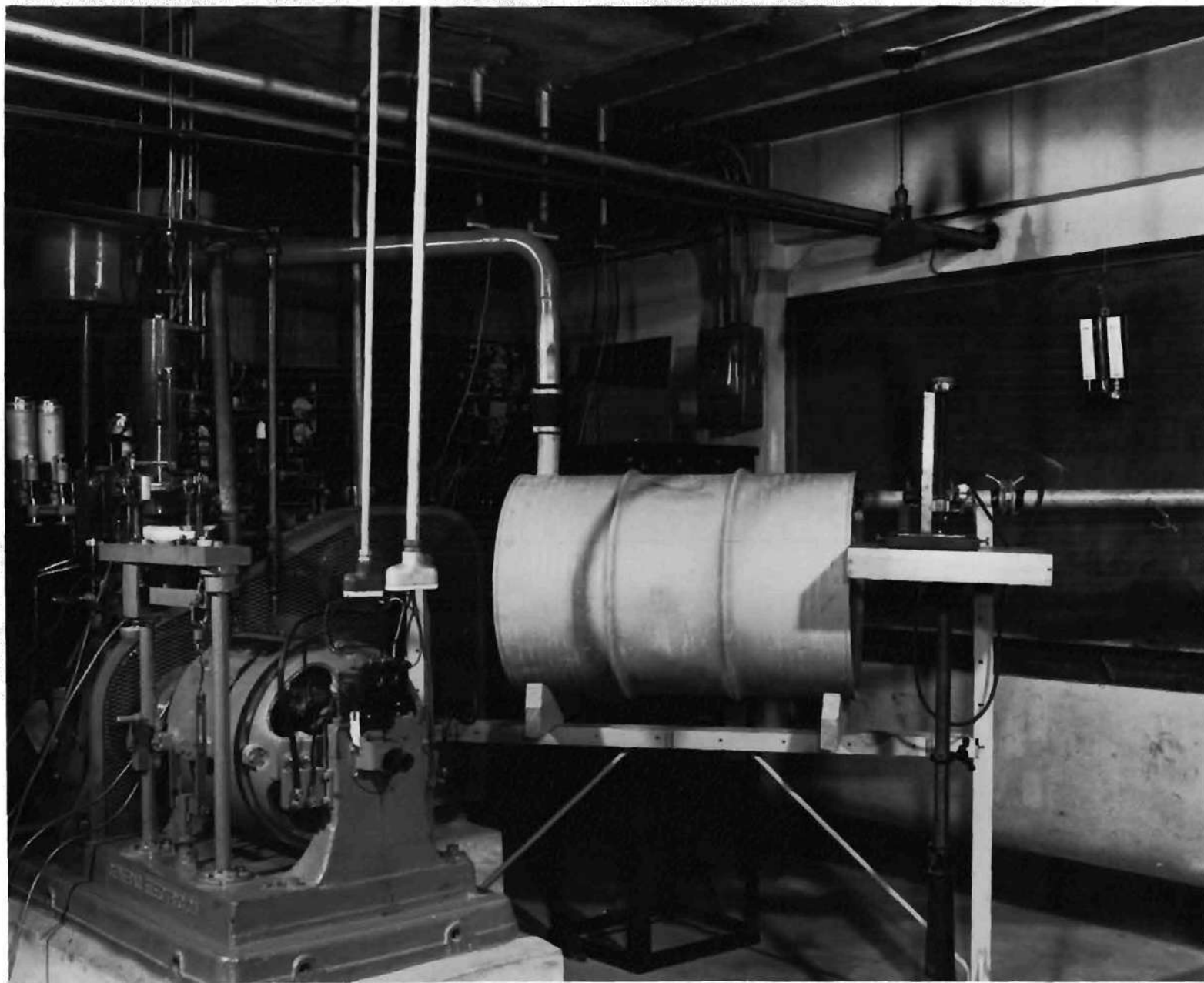


FIGURE 2

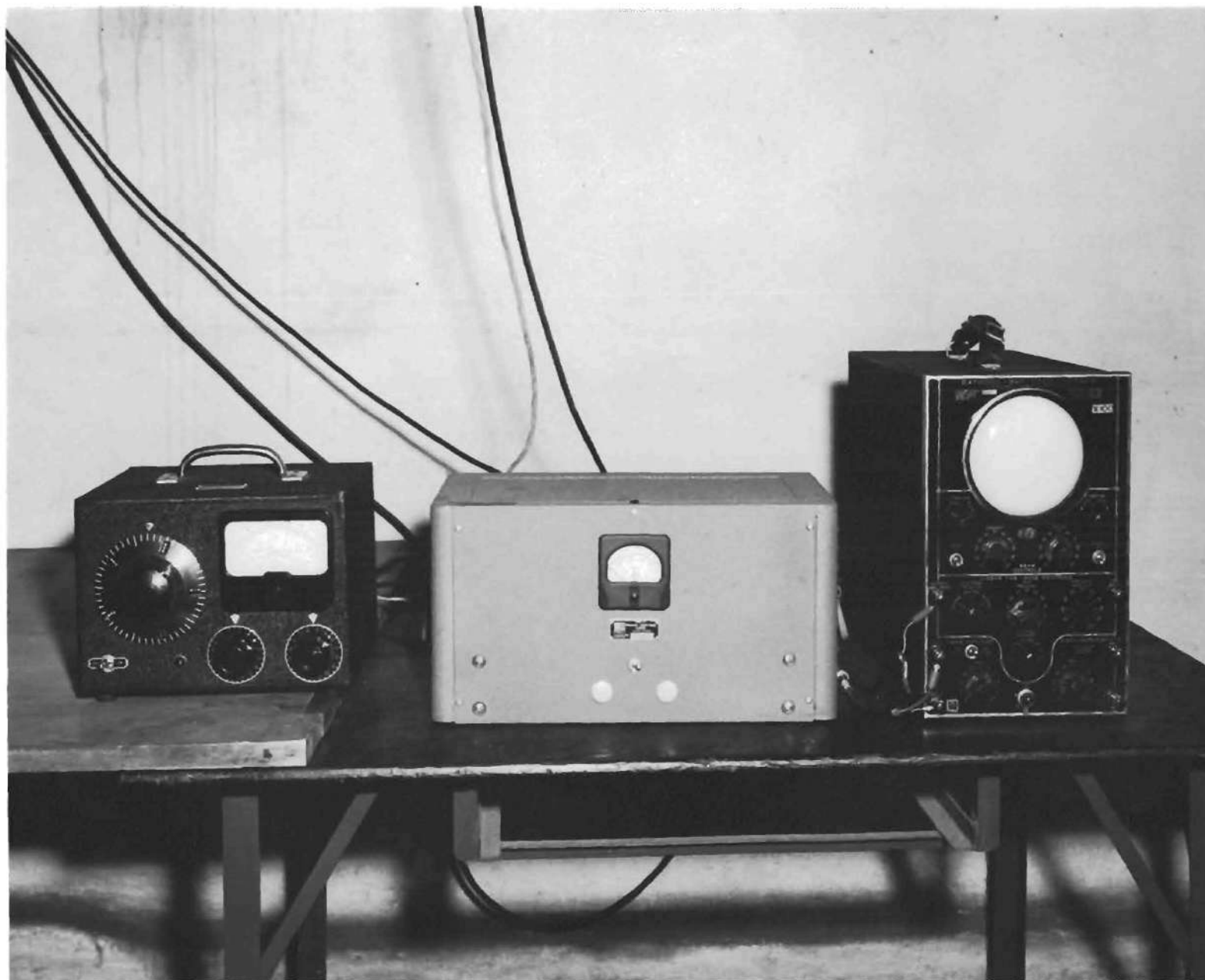


FIGURE 3

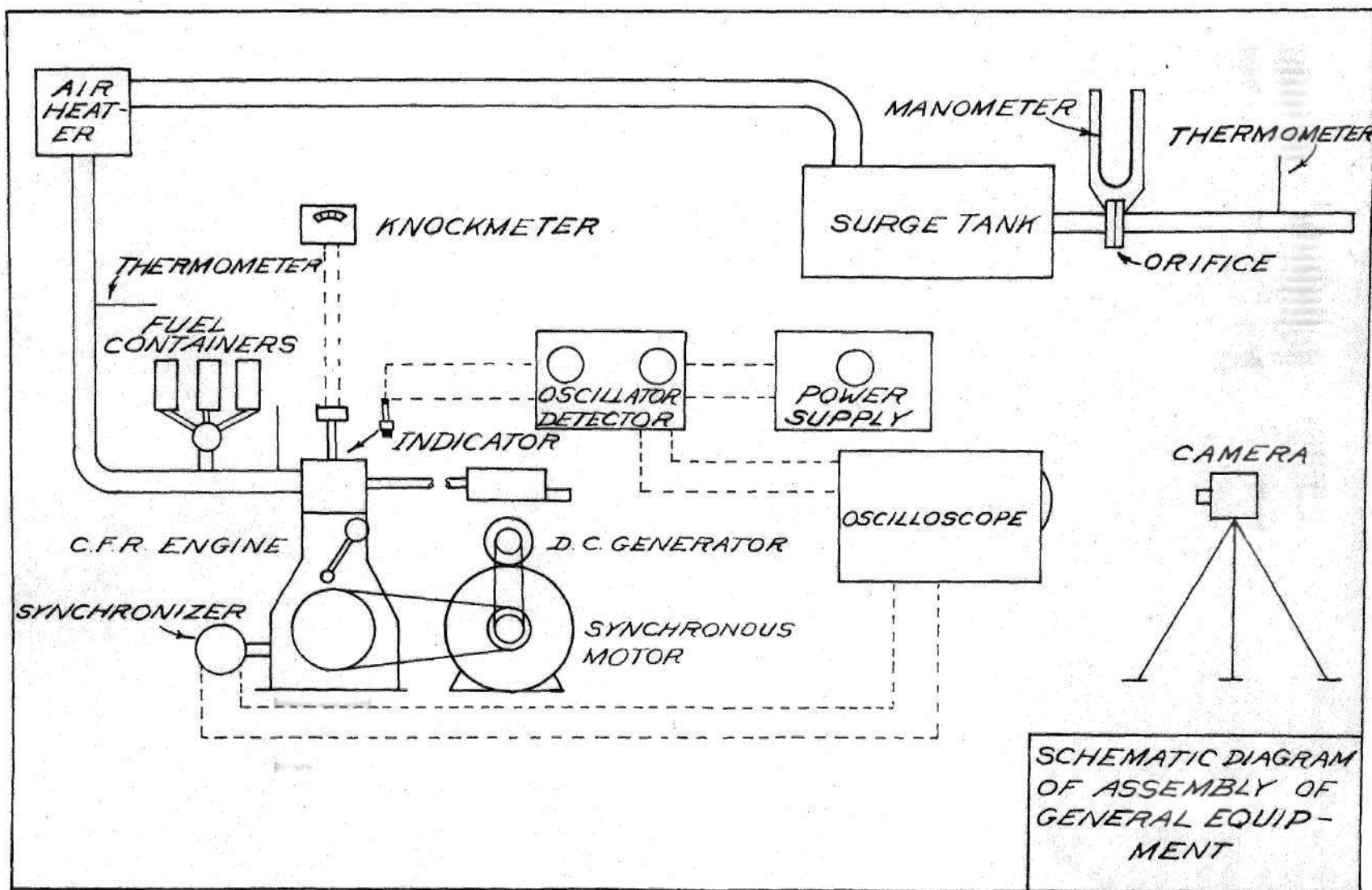


FIGURE 4

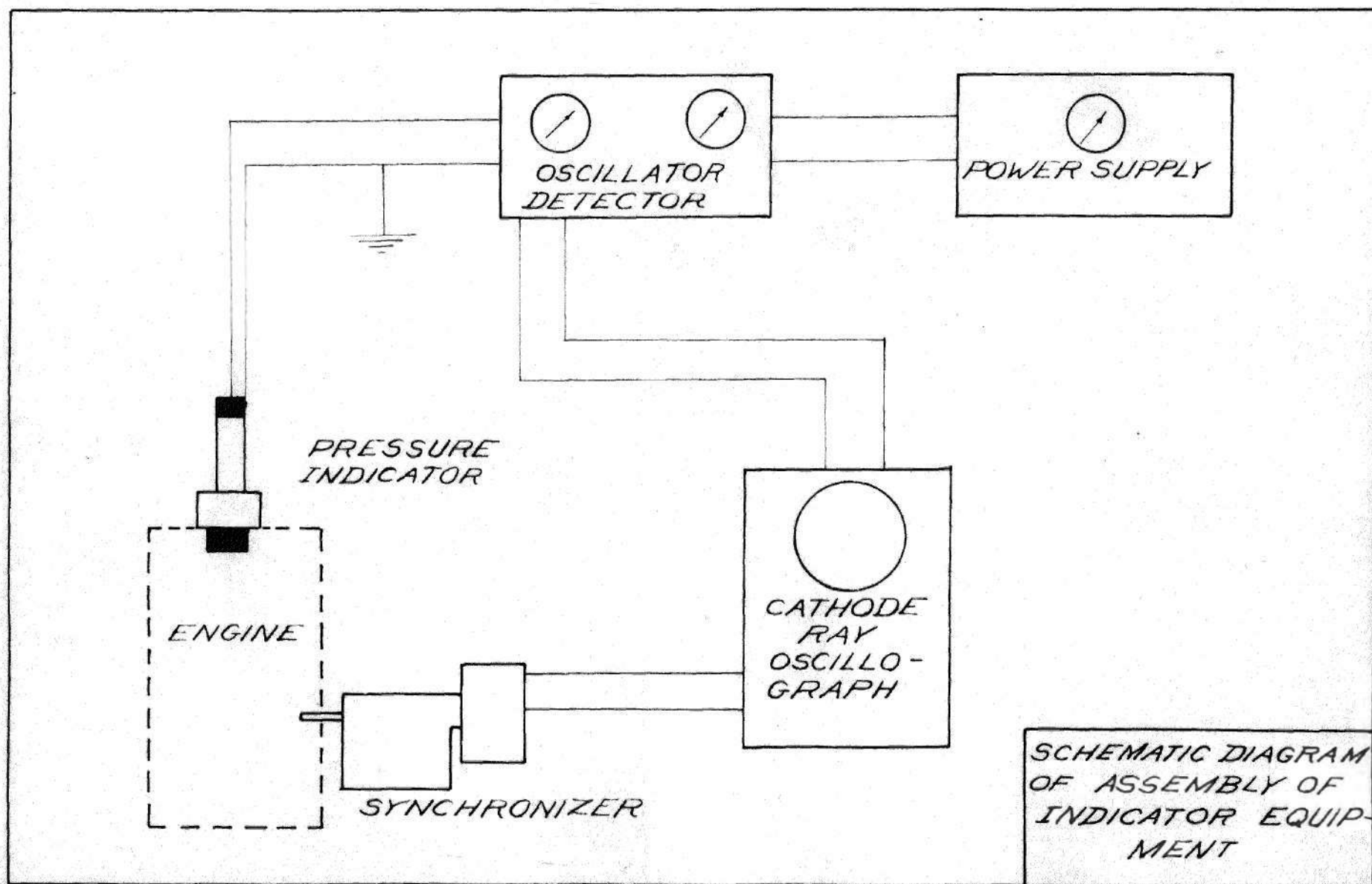


FIGURE 5



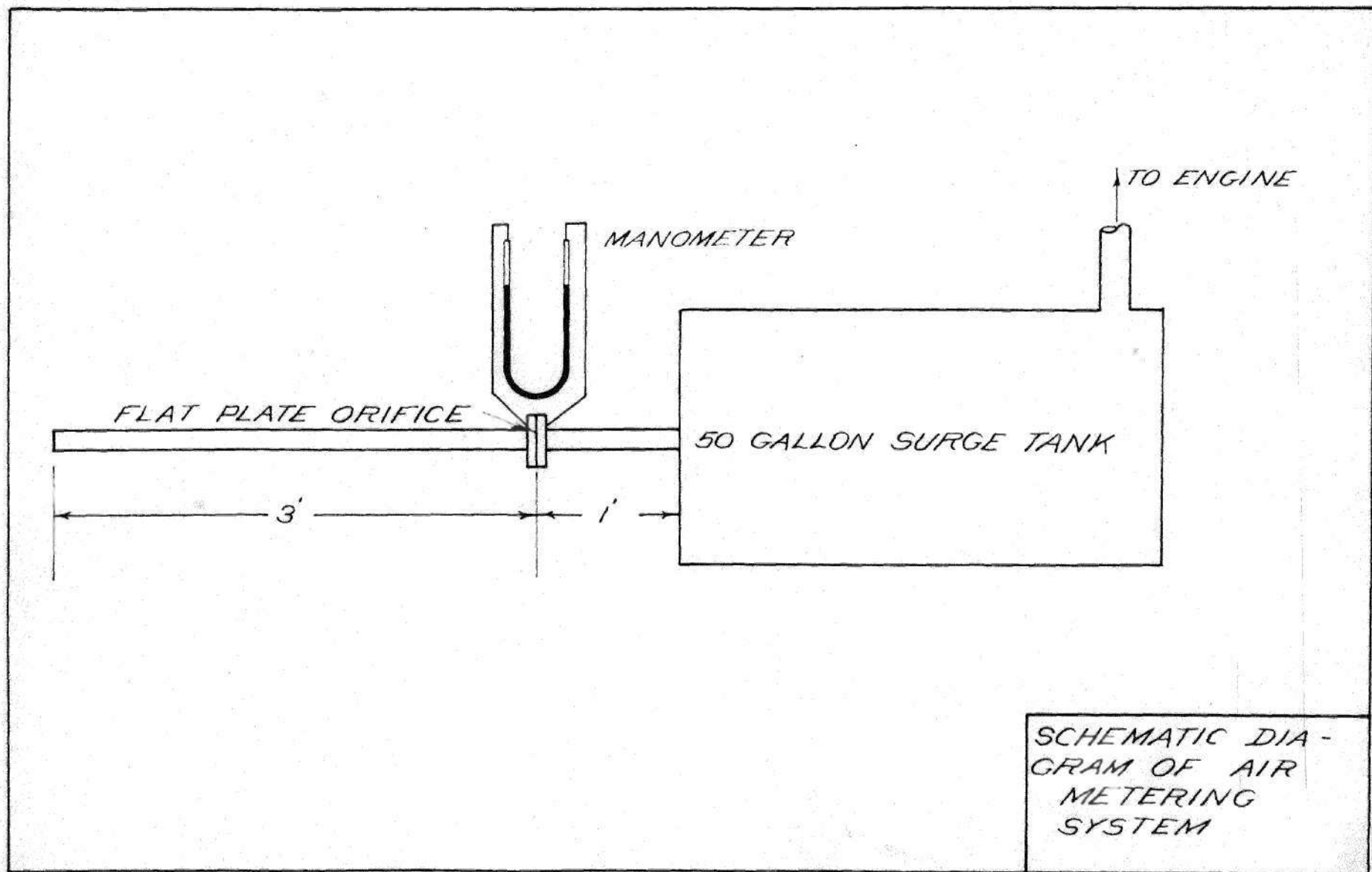


FIGURE 6

Table I  
SAMPLE DATA SHEET

RUN	XII						
Reading	1	2	3	4	5	6	Avg.
Wet bulb Temp. °F.	78.0	78.0	78.0	78.0	78.0	73.0	78.0
Dry bulb Temp. °F.	89.0	90.0	90.0	90.0	90.0	90.0	90.0
Barometric press. in Hg.	29.005	29.005	29.005	29.005	29.005	29.005	29.005
Fuel: a. Kind	C-14	C-14	C-14	C-14	C-14	C-14	C-14
b. Density 92/ml.	0.715	0.715	0.715	0.715	0.715	0.715	0.715
Time min.-sec.	0.0	5.0	10.0	15.0	20.0	22.10	22.10
Knockmeter	64.0	70.0	62.0	67.0	66.0	66.0	64.9
Oil Pressure	38.0	38.0	38.0	38.0	38.0	38.0	38.0
Oil Temp.	107	108	110	111	112	112	109.8
Instrument Panel D.C. Gen. volts	70	70	70	70	70	70	70
Manifold Heater A.C. Amps.	2.25	2.25	2.25	2.25	2.25	2.25	2.25
Air Heater A.C. Amps.	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fuel level	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Fuel burned	0	-	-	-	-	-	-
Air temp. after heater	112	113	114	115	115	115	114
Fuel - Air Mixture temp.	201	203	203	204	205	205	203.5
Coolant Temp.	209	209	209	209	209	208	209
Spark Setting °BTDC	20	20	20	20	20	20	20
Micrometer Setting	.417	.434	.434	.434	.434	.434	.434
Bouncing pin setting	5.15	5.15	5.15	5.15	5.15	5.15	5.15
RPM	901	901	901	901	902	902	901.3
Pressure drop across orifice in alcohol	0.5566	0.5566	0.5566	0.5588	0.5588	0.5588	0.5577
Air temp. before surge tank	89.0	89.5	89.0	89.0	89.5	89.5	89.25
Oscillator Detector							
a. Volts	223						223
b. Milliamperes	0.28						0.28
c. Gain Setting	1.5						1.5
d. Position Setting	7						7
Power Supply volts	325						325
Oscilloscope							
a. Input switch, under	250						250
b. Y-axis gain	12						12
c. Sync. Selector	Ext						Ext
d. Sync. Amplitude	70						70
e. Intensity	79						79
f. Focus	43						43
g. Frequency course	8-72						8-72
h. x-Axis gain	22.2						22.2
i. Picture numbers	Pack 4						Pack 4
Synchronizer setting	1,2,3,4						1,2,3,4
	BDC						BDC

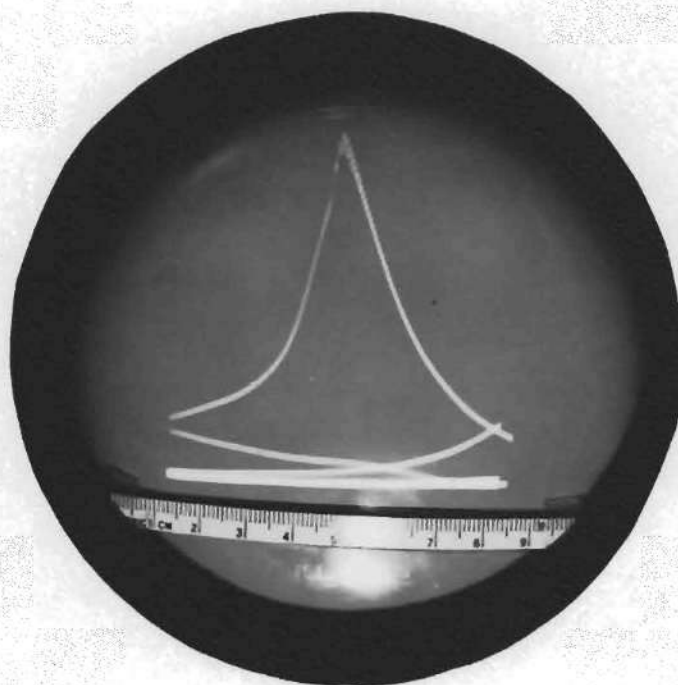


## AVERAGE DATA

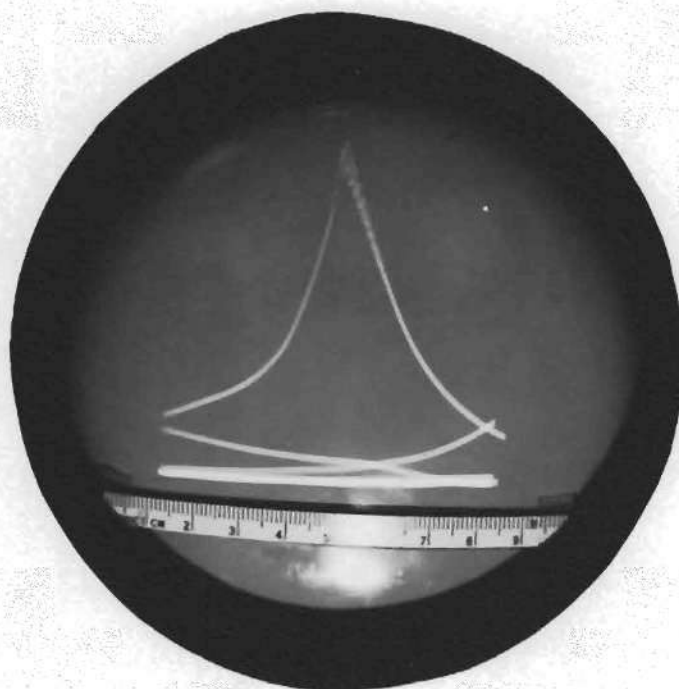
RUN	VII	VIII	IX	X	XI	XII	XIII	XIV
Wet bulb temp. °F.	77.3	78.8	75.4	77.7	77.9	78.0	79.25	79
Dry bulb temp. °F.	88.3	90.0	83.4	87.7	88.5	90.0	91.6	92
Barometric press. in Hg.	29.2	29.2	29.005	29.005	29.005	29.005	29.005	29.005
Fuel: a. Kind	C-14	C-14	C-14	C-14	C-14	C-14	C-14	C-14
b. Density grams/ml.	0.715	0.715	0.715	0.715	0.715	0.715	0.715	0.715
Time min.-sec.	26.15	28.5	24.43	22.40	22.45	22.10	23.7	22.49
Knockmeter	30.97	48.9	68.7	94.54	78.3	64.9	46.9	97.9
Oil Pressure psi	39.0	38.5	39.7	38.1	38.8	38.0	38.0	38.0
Oil Temp. °F.	96.6	110.3	91.9	105.5	100.7	109.8	115.0	117.6
Instrument panel D.C. Gen. volts.	69.0	69.1	70	70	70	70	70	70
Manifold heater A.C. Amps.	2.3	2.3	2.2	2.20	2.25	2.25	2.3	2.3
Air Heater A.C. Amps.	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fuel level	2.0	2.3	2.61	1.50	1.50	1.50	1.50	1.50
Fuel burned ml.	400	400	400	400	400	400	400	400
Air temp. after heater	110.9	114.1	107.3	111.3	112.8	114.0	117.8	116.8
Fuel - Air mixture temp.	199.4	201.0	200.3	198.8	197.3	203.5	208.0	206.0
Coolant temp.	209.0	209.0	209.0	209.0	209.0	209.0	209.0	209.0
Spark setting °BTDC	20	20	20	20	20	20	20	20
Micrometer setting	.400	.300	.200	.402	.412	.434	.4495	.410
Bouncing pin setting	5.15	5.15	5.15	5.15	5.15	5.15	5.15	5.15
RPM	900	896.4	897.7	897.3	900	901.3	898.7	900.6
Pressure drop across orifice in alcohol	.5726	.6694	.5746	.5590	.5607	.5577	.5623	.5619
Air temp. before surge tank	87.3	88.6	83.3	86.5	88.2	89.25	91.0	92.0
Oscillator Detector								
a. Volts	223	223	223	223	223	223	223	223
b. Milliamperes	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
c. Gain setting	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
d. Position Setting	7	7	7	7	7	7	7	7
Power Supply volts	325	325	325	325	325	325	325	325
Oscilloscope								
a. Input switch, under	250	250	250	250	250	250	250	250
b. Y-axis gain	12	12	12	12	12	12	12	12
c. Sync. Selector	Ext.	Ext.	Ext.	Ext.	Ext.	Ext.	Ext.	Ext.
d. Sync. Amplitude	70	70	70	70	70	70	70	70
e. Intensity	79	79	79	79	79	79	79	79
f. Focus	43	43	43	43	43	43	43	43
g. Frequency	8-72	8-72	8-72	8-72	8-72	8-72	8-72	8-72
h. x-Axis gain	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2
i. Picture numbers	2nd		3rd			4th		
Synchronizer setting	5,6,7,8 BDC	9,10,11,12 BDC	1,2,3,4 BDC	5,6,7,8 BDC	9,10,11,12 BDC	1,2,3,4 BDC	5,6,7,8 BDC	9,10,11,12 BDC

## OSCILLOSCOPE PICTURES, RUN XII

PACK 4



PICTURE 1



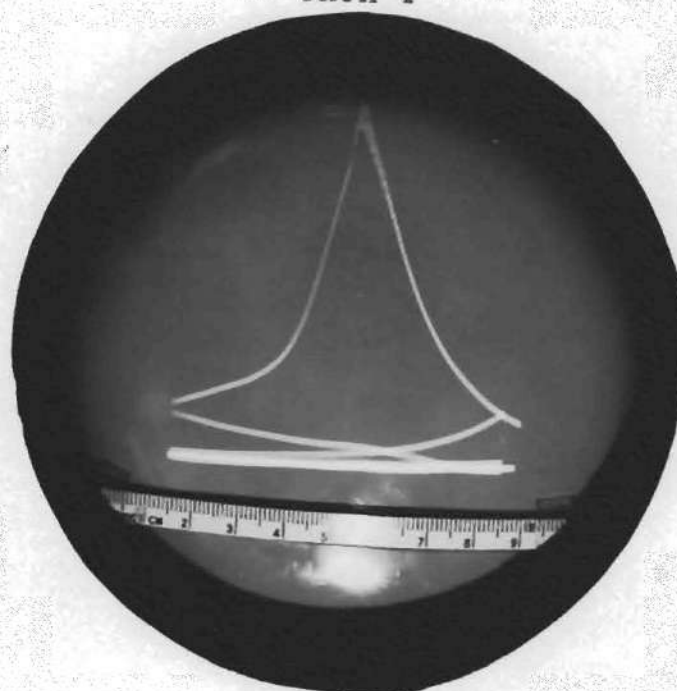
PICTURE 2

FIGURE 7

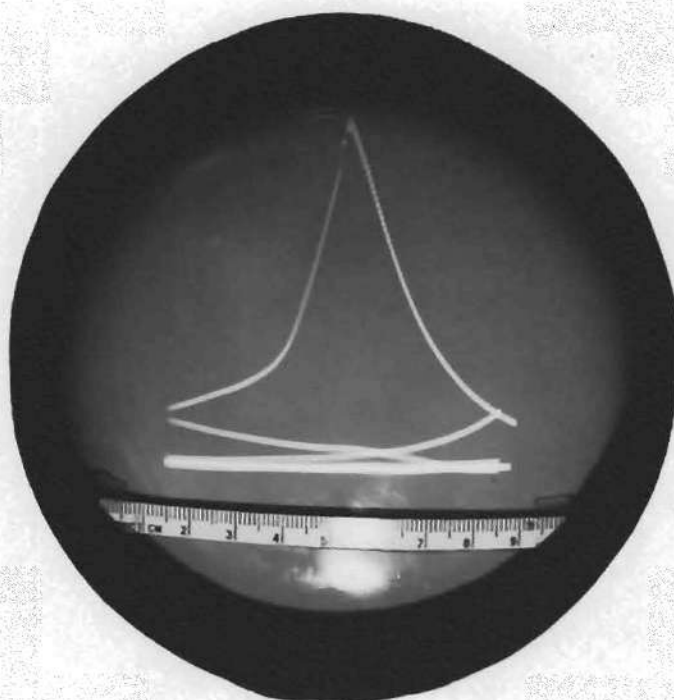


## OSCILLOSCOPE PICTURES, RUN XIII

PACK 4



PICTURE 5



PICTURE 6

FIGURE 8

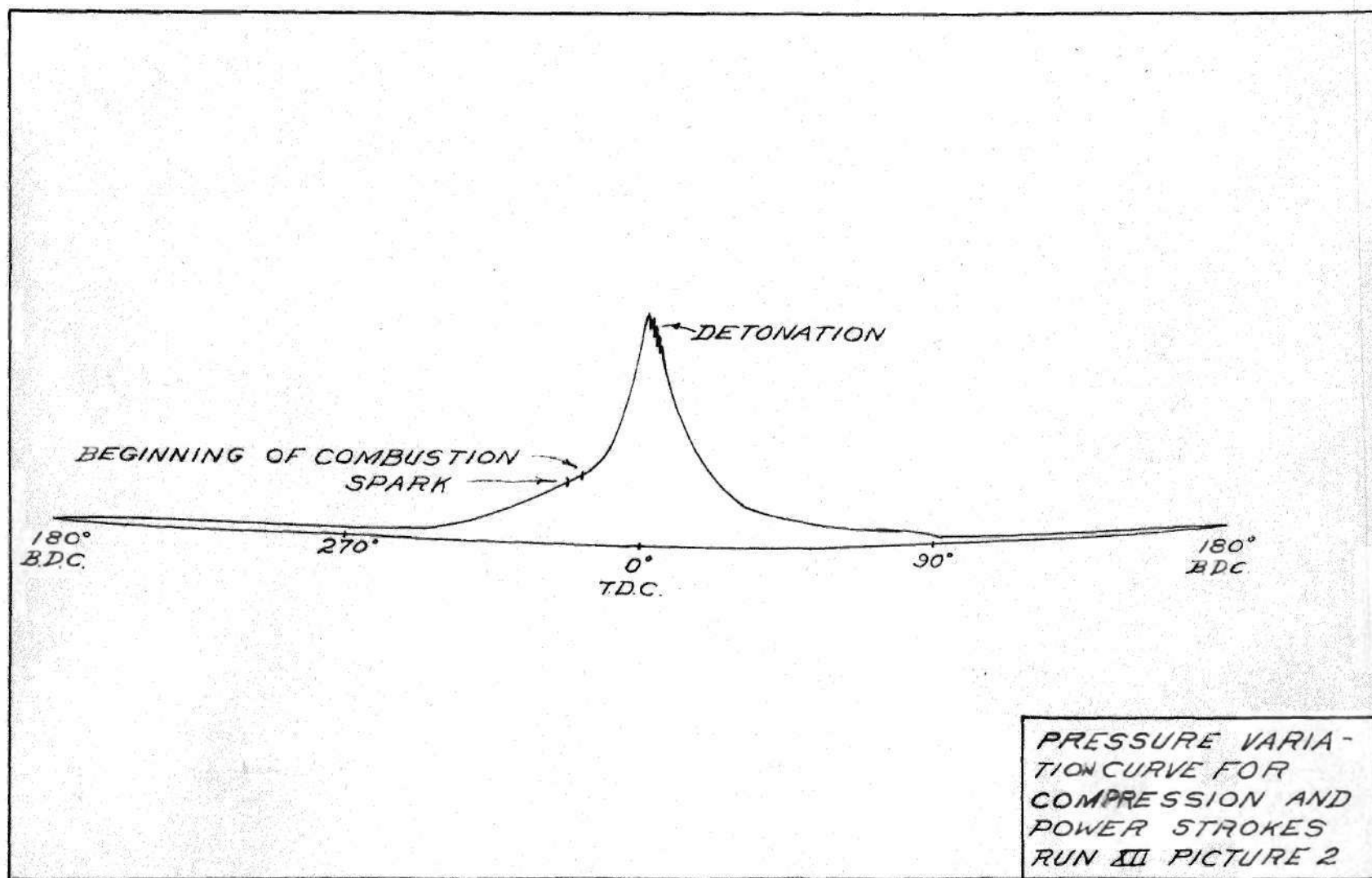


FIGURE 9

TABLE III  
TABULATION OF RESULTS

RUN	KNOCK INTENSITY	FLAME DENSITY
VII	30.97	0.2965
VIII	48.90	0.2690
IX	68.70	0.2465
X	94.54	0.1990
XI	78.30	0.2490
XII	64.90	0.1740
XIII	46.90	0.2273
XIV	97.90	0.1344

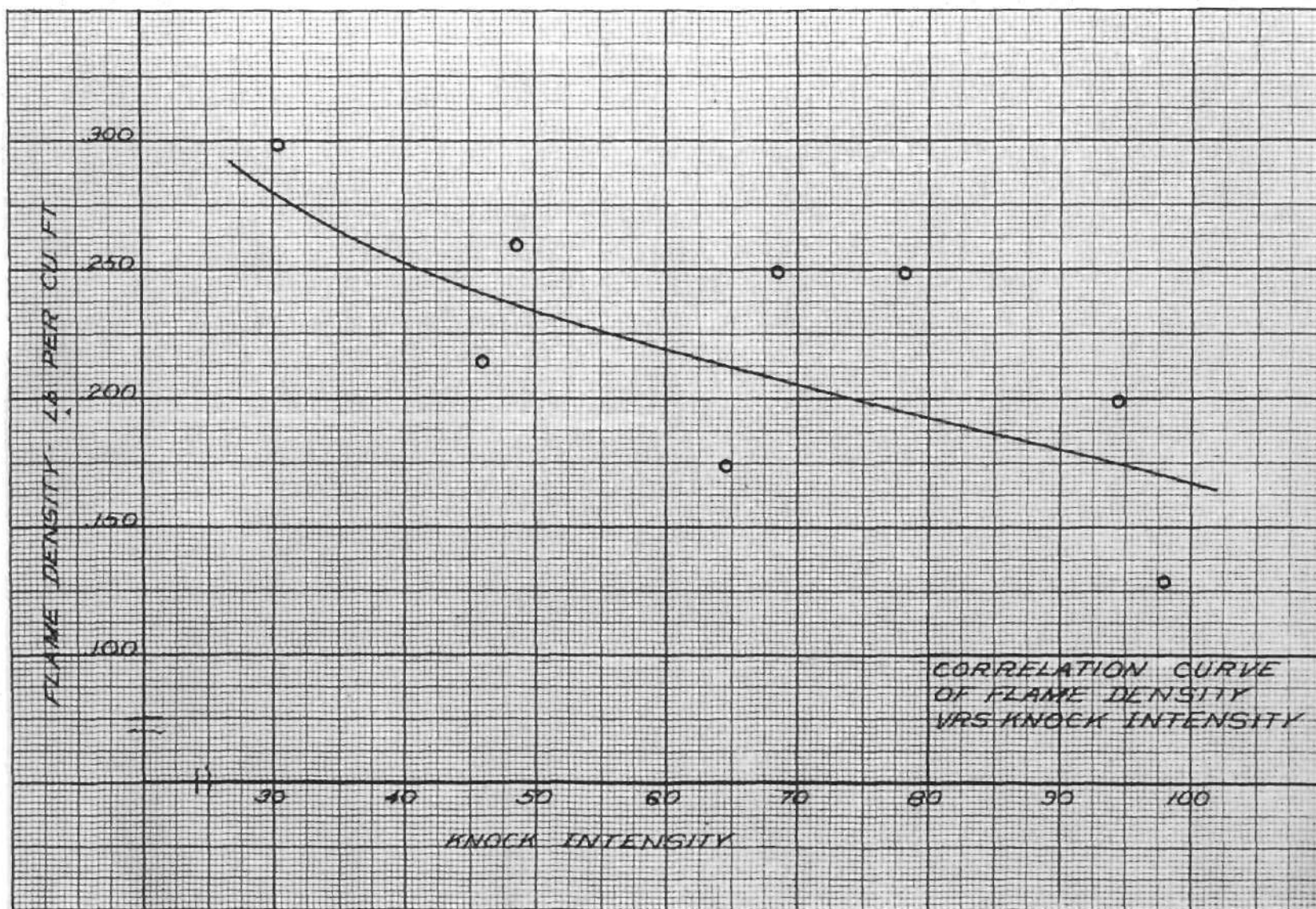


FIGURE 10



## DISCUSSION

The first test runs were made using an R. C. A. 9 inch cathode-ray oscilloscope to indicate the pressure variations in the combustion chamber. However, after several runs, the image on the oscilloscope screen became distorted and irregular and on investigation it was discovered that the transformer within the scope was overheating. A Dumont 208, five inch oscilloscope was substituted in place of the R. C. A. instrument, and this smaller oscilloscope functioned very satisfactorily although giving a smaller image.

Another difficulty which was encountered in making the test runs, and one which caused a change in operating procedure was the failure of the auxiliary motor-generator set which powered the loading dynamometer when it was being used as a motor to start the C.F.R. Engine. Upon failure of the M-G set it was decided to disconnect the dynamometer and connect the C.F.R. Engine by belts to the synchronous motor which had been used along with a small generator to supply power to the engine instrument panel. Thus, with the dynamometer disconnected it was not possible to apply a load to the engine, so it became necessary to vary the knock intensity by varying the compression ratio and the fuel level. This method proved very satisfactory.

In adjusting the apparatus for the test runs the

bouncing pin was so set that within a range of medium audible detonation the knock meter would vary from zero to 100. It should be noted that this knock intensity indicated by the knockmeter has no units and is of significance only when compared to other knockmeter readings at the same bouncing pin setting.

It will be noted in the pictures of the image on the oscilloscope screen (Figures 7 and 8) that the pressure-variation diagram is broken into five parts. This gives a much larger diagram when each part is connected (Figure 9). The start of the diagram is at bottom dead center since the synchronizer was so set that its electrical impulse was sent out at this position of the crankshaft. This electrical impulse when sent into the synchronizing poles of the oscilloscope initiated the sweep of the image, and the current from the pressure indicator plug entering the y-axis poles produced the vertical deflection which was proportional to the magnitude of the pressure on the plug diaphragm. The effect of the synchronizer was to produce an image which remained stationary so that little trouble would be encountered when taking pictures of the image.

The metric scale mounted on the face of the oscilloscope facilitated the measuring of the ordinates which, when used along with the calibration curve for the indicator apparatus, (Figure 14), gave the magnitudes of the pressures which



were necessary to calculate the flame density.

In calculating the flame density it was arbitrarily decided to take the instantaneous pressure of the combustion gases at a crank position of six degrees before top dead center.

## CONCLUSIONS

The results of this test are given in Table III on page 24, and a graph of these results is shown in Figure 10 on page 25. Upon study of the graph it is concluded that there is some correlation between the flame density and the knock intensity. The curve indicates that as the flame density increases the knock intensity decreases. Thus it might be possible to so control the factors affecting flame density as to increase this flame density, the result being a decrease in a knock intensity.

It is suggested that with the above results in mind further study of the same type be conducted so as to collect sufficient data in order that a more exact correlation of flame density and knock intensity may be determined. If further study be made it is suggested that a more accurate and thorough method of calibrating the indicator apparatus be used. Also, changes should be made which would make possible the recording of the knock intensity and pressure variations at the same time, rather than have to stop the engine and replace the bouncing pin with the indicator plug and then record the pressure variations after again starting the engine.



## BIBLIOGRAPHY

- Baker, A. W., Jr., A Comparison of Various Vegetable Oils As Fuels for Compression Ignition Engines, a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering, the Georgia School of Technology, Atlanta, Georgia, 1946.
- Bone, William A. and Townend, Donald T. A., Flame and Combustion in Gases, Longman's Green and Co. Ltd., 1939.
- Bone, William A., Newitt, Dudley M., and Towend, Donald, T. A., Flame and Combustion in Gases, Longman's Green and Col, London, 1929.
- Draper, C. S., The Physical Effects of Detonation in a Closed Cylindrical Chamber, N.A.C.A. Report 727, 1942.
- Goodenough, G. A. and Felbec, G. T., An Investigation of the Maximum Temperature and Pressures Attainable in the Combustion of Gaseous and Liquid Fuels, Bulletin number 39, Engineering Experiment Station, University of Illinois.
- Leary, W. A. and Taylor, E. S., The Significance of the Time Concept in Engine Detonation, N. A. C. A., Wartime Report, W-32, 1943.
- Li Yao Tzu, Physical Aspect of Detonation in Aircraft Engines with Spherical Combustion Chamber, Doctor's Thesis, M. I. T., 1939.
- Ower, E., The Measurement of Air Flow, Chapman and Hall, Ltd., 11 Henrietta Street, London, 1927.
- Rothrock, A. M. and Biermann, A. E., The Knocking Characteristics of Fuels in Relation to Maximum Permissible Performance of Aircraft Engines, N.A.C.A. Report number 655, 1939.
- Taylor, E. S., Leary, W. A., and Diver, J. R., Effect of Fuel-Air Ratio, Inlet Temperature, and Exhaust Pressure on Detonation, N.A.C.A., Report Number 699, 1940.

APPENDIX I  
DERIVATION OF RELATION FOR DETERMINING  
FLAME DENSITY<sup>3</sup>

Symbols and Abbreviations:

$A_1$  is the instantaneous area of the flame in square feet.

$a$  is  $\frac{P_0}{P_1}$

$d_1$  is the instantaneous density of the flame in pounds per cubic foot.

$M$  is  $\frac{\bar{w}_1}{\bar{w}_t}$  is fractional weight burned.

$N$  is  $\frac{V_1}{V_t}$  is fractional volume burned.

$n$  is 1.35

$n_m$  is the ratio of the specific heat of the mixture at constant pressure to that at constant volume.

$n_p$  is the ratio of the specific heat of the products at constant pressure to that at constant volume.

$P_0$  is the pressure after reaction in pounds per square foot absolute.

$P_1$  is initial pressure in pounds per square foot absolute.

$P_2$  is the pressure of the unburned gases after expansion in pounds per square foot absolute.

$P_i$  is pressure of burned gases after expansion in pounds per square foot absolute.

---

<sup>3</sup>Unpublished notes by Dr. R. L. Sweigert, Georgia Institute of Technology.

$T_0$  is the absolute temperature after reaction in degrees Fahrenheit.

$T_1$  is the absolute temperature in degrees Fahrenheit.

$T_2$  is the absolute temperature of the unburned gases after expansion.

$T_i$  is the absolute temperature of the burned gases after expansion in degrees Fahrenheit.

$V_1$  is the volume after reaction in cubic feet.

$V_i$  is the volume of burned gases after expansion in cubic feet.

$V_t$  is the initial volume in cubic feet.

$V_t - V_i$  is the volume of the unburned gases after expansion in cubic feet.

$v_1$  is the specific volume of initial gases in cubic feet per pound.

$v_2$  is the specific volume of burned gases in cubic feet per pound.

$v_i$  is the instantaneous volume of the flame in cubic feet.

$V_{si}$  is the instantaneous velocity of the flame in feet per second.

$W_c$  is the work of compression.

$W_e$  is the work of expansion.

$W_r$  is the weight-rate of burning of gases in combustion chamber.

$\bar{w}_t$  is the weight of all gases in chamber at initial conditions in pounds.

$\bar{w}_u$  is the weight of unburned gases in the cylinder in pounds.

$y$  is  $\frac{P_i}{P_l}$



Derivation:

$$\text{Assume } P_2 = P_1$$

$$\text{Assume } W_e = W_c$$

$$\text{And since } V_1 = V_o$$

From thermodynamics for adiabatic expansion and compression:

$$W_e = \frac{P_1 V_1 - P_o V_1}{1 - n_p} \quad (1)$$

$$-W_c = \frac{P_1 (V_t - V_1) - P_1 (V_t - V_1)}{1 - n_m} \quad (2)$$

$$\text{And since } W_e = W_c$$

$$\frac{P_1 V_1 - P_o V_1}{1 - n_p} = \frac{P_1 (V_t - V_1) - P_1 (V_t - V_1)}{1 - n_m} \quad (3)$$

Dividing equation (3) by  $P_1$  gives:

$$\left[ \frac{P_1}{P_1} V_1 - \frac{P_o}{P_1} V_1 \right] \left[ \frac{1 - n_m}{1 - n_p} \right] = \left[ \frac{P_1}{P_1} (V_t - V_1) - \frac{P_1}{P_1} (V_t - V_1) \right] \quad (4)$$

$$\text{taking } \frac{P_o}{P_1} = a; \quad \frac{P_1}{P_1} = y \quad \text{and} \quad \frac{1 - n_m}{1 - n_p} = \delta$$

Then equation (4) becomes:

$$(yV_1 - aV_1)\delta = -[y(V_t - V_1) - (V_t - V_1)] \quad (5)$$

Rearranging and transposing, equation (5) becomes:

$$yV_1(\delta - 1) = V_1(a\delta - 1) + V_t(1 - y) \quad (6)$$

Also, from thermodynamics:

$$P_1 (V_t - V_1)^{n_m} = P_1 (V_t - V_1)^{n_m} \quad (7)$$

then from (7), solving for  $V_1$  gives:

$$V_1 = V_t - y^{1/n_m} (V_t - V_1)$$

Substituting this value of  $V_1$  into equation (6) gives:

$$yV_1(\delta - 1) = V_t - y^{\frac{1}{n}}(V_t - V_1) \quad [(\alpha\delta - 1) \neq V_t(1-y)] \quad (8)$$

Solving equation (8) for  $V_1$  gives:

$$V_1 = V_t \frac{(\alpha\delta - y) - y^{\frac{1}{n}}(\alpha\delta - 1)}{y(\delta - 1) - y^{\frac{1}{n}}(\alpha\delta - 1)} \quad (9)$$

$$\text{Since } V_t - V_1 = \bar{w}_u v_1$$

$$\text{and } V_t - V_1 = \bar{w}_u v_2$$

$$\text{but } V_1 = \frac{V_t}{\bar{w}_t}$$

$$\text{and } v_2 = \frac{V_t - V_1}{\bar{w}_t - \bar{w}_1}$$

$$\text{And since } P_1(V_t - V_1)^n = P_1(V_t - V_1)^n$$

$$\text{then } P_1 \bar{w}_u^n \left( \frac{V_t}{\bar{w}_t} \right)^n = P_1 \bar{w}_u^N \left( \frac{V_t - V_1}{\bar{w}_t - \bar{w}_1} \right)^n$$

$$\text{and } P_1^{\frac{1}{n}} \bar{w}_u \left( \frac{V_t}{\bar{w}_t} \right) = P_1^{\frac{1}{n}} \bar{w}_u \left( \frac{V_t - V_1}{\bar{w}_t - \bar{w}_1} \right) \quad (10)$$

Rearranging, transposing and substituting:

$$y^{\frac{1}{n}} \text{ for } \left( \frac{P_1}{P_1} \right)^{\frac{1}{n}} \text{ in (10) gives:}$$

$$\frac{\bar{w}_t - \bar{w}_1}{\bar{w}_t} = y^{\frac{1}{n}} \frac{(V_t - V_1)}{\left( \frac{V_t}{\bar{w}_t} \right)} \quad (11)$$

$$\text{and } 1 - \frac{\bar{w}_1}{\bar{w}_t} = -y \frac{1}{n} \left(1 - \frac{V_1}{V_t}\right) \quad (12)$$

$$\text{Taking } \frac{\bar{w}_1}{\bar{w}_t} = M \text{ and } \frac{V_1}{V_t} = N$$

Substituting these into relation (12) gives:

$$1 - M = y \frac{1}{n} (1 - N)$$

$$\text{and } M = 1 - y \frac{1}{n} (1 - N) \quad (13)$$

$$\text{Since } \bar{w}_r = A_1 V_{s1} d_1$$

$$\text{and } d\bar{w}_1 = dV_1 d_1$$

$$\text{then } d_1 = \frac{d\bar{w}_1}{dV_1}$$

$$\text{thus } \bar{w}_r = A_1 V_{s1} \frac{d\bar{w}_1}{dV_1} \quad (14)$$

Since from equation (12)

$$1 - \frac{\bar{w}_1}{\bar{w}_t} = y \frac{1}{n} \left(1 - \frac{V_1}{V_t}\right)$$

Multiplying through by  $\bar{w}_t$  gives:

$$\bar{w}_t - \bar{w}_1 = y \frac{1}{n} \left( \bar{w}_t - \frac{\bar{w}_t}{V_t} V_1 \right) \quad (15)$$

$$\text{But } \frac{\bar{w}_t}{V_t} = d_1 = \text{initial density}$$

Therefore

$$\bar{w}_t - \bar{w}_1 = y^{\frac{1}{n}}(w_t - d_1 V_1) \quad (16)$$

Differentiating equation (16) gives:

$$d\bar{w}_1 = \frac{\bar{w}_t}{n} y^{\frac{1-n}{n}} \left( \frac{V_1}{V_t} - 1 \right) dy + d_1 y^{\frac{1}{n}} dV_1 \quad (17)$$

$$\text{But } \frac{V_1}{V_t} = N$$

$$\text{Therefore } d\bar{w}_1 = \frac{w_t}{n} y^{\frac{1-n}{n}} (N-1) dy + d_1 y^{\frac{1}{n}} dV_1 \quad (18)$$

Dividing equation (18) by  $dV_1$  gives:

$$\frac{d\bar{w}_1}{dV_1} = \frac{\bar{w}_t}{n} y^{\frac{1-n}{n}} (n-1) \frac{dy}{dV_1} + d_1 y^{\frac{1}{n}} \quad (19)$$

Rearranging gives:

$$\frac{d\bar{w}_1}{dV_1} = d_1 y^{\frac{1}{n}} \left[ \frac{n-1}{n} y^{-1} \frac{dy}{dV_1} + 1 \right] \quad (20)$$

$$\text{But } \frac{dV_1}{V_t} = dN$$

$$\text{Therefore } \frac{d\bar{w}_1}{dV_1} = d_1 y^{\frac{1}{n}} \left[ \frac{(N-1)}{N} y^{-1} \frac{dy}{dN} + 1 \right] \quad (21)$$

But, assuming  $\delta = 1$  then from equation (9)

$$N = 1 - \frac{a-y}{y^{\frac{1}{n}}(a-1)} \quad (22)$$



Differentiating equation (22) gives:

$$\frac{dy}{dN} = \frac{\frac{1}{n} (a - 1)}{(n-1) \cancel{ay}} = 1 \quad (23)$$

Substituting right hand number at equation (23) for  $\frac{dy}{dN}$  in equation (21) gives:

$$\frac{d\bar{w}_i}{dV_i} = d_1 y^{\frac{1}{n}} \left[ 1 - \frac{a - y}{a \cancel{y} (n-1)} \right] \quad (24)$$

But  $\frac{d\bar{w}_i}{dV_i} = \text{flame density} = d_1$

therefore

$$d_1 = d_1 y^{\frac{1}{n}} \left[ 1 - \frac{a - y}{a \cancel{y} (n-1)} \right] \quad (25)$$

APPENDIX II  
EQUIPMENT

A. Fuel Research Engine

Bore: 3.25 inches

Stroke: 4.50 inches

Date: March 1948

Serial number: 683759

Manufactured by: Waukesha Motor Company

B. Synchronous Induction Motor

Type: HS 1324

Serial number: 249866

R.P.M.: 1200

Cycles: 60

Phase: 3

Manufactured by: Harnischfeger Corporation  
Milwaukee, Wisconsin

C. D. C. Generator

Type: B C

Model: 5BC66AB906A

R.P.M.: 1800

Manufactured by: General Electric

D. Synchronizer

Type: Boston Reductor

Serial number: 244695

Manufactured by: Boston Gear Works  
North Quincy, Massachusetts

## E. Pressure Indicator Plug

Type: Condenser

## F. Oscillator Detector Unit

Serial Number: LCOD 149

Manufactured by: Research Laboratory Division  
General Motors

## G. Power Supply Unit

Serial number: IOPS 149

Manufactured by: Research Laboratory Division  
General Motors

## H. Oscilloscope

Type: Cathode Ray Tube, 208

Serial number: 770

Volts: 115/230

Cycles: 40/60

Watts: 90

Manufactured by: Dumont

## I. Camera

Type: Speed Graphic

Manufactured by: The Folmer Graflex Corporation

## J. Micromanometer

## K. Thermometers

Type: Mercury-in-glass.

## L. Fuel

Type: Secondary Reference Fuel, C-14

Manufactured by: Enjay Company, Inc., 15 W. 51st Street,  
New York 19, New York



# AIR METERING SYSTEM

To measure the quantity of air taken in on the intake stroke of the engine, an orifice of the dimensions shown in Figure 11 was used. The installation details are shown in Figure 12.

The orifice was installed between flanges in a pipe line of  $1\frac{1}{2}$  inches nominal diameter. The inside diameter of the pipe was 1.61 inches and the diameter of the orifice was 0.805 inches. This gives a ratio of areas of four. Downstream from the orifice a 50 gallon drum was installed to serve as a surge tank to insure a steady flow of air through the orifice.

The expansion of the air was assumed to obey the equation for a perfect gas with an isentropic expansion.

$$PV^k = K \quad (1)$$

where P is the pressure in pounds per square foot absolute

V is the volume in cubic feet

k is the ratio of the specific heat of the air at constant pressure to the specific heat at constant volume.

K is a constant.

Assuming that equation (1) represents the process and also that the same weight of air passes each point in the intake line, the following relation can be derived.



$$q = a g \sqrt{\frac{2 p r^2 (P_1 - P_2)}{r^2 - 1}} \quad (2) \quad \times C$$

where  $q$  is the theoretical rate of flow in pounds per second.

$a$  is the area of the orifice in square feet.

$\rho$  is the density of the air in slugs per cubic foot.

$r$  is the ratio of the pipe area to the orifice area.

$P_1 - P_2$  is the pressure drop across the orifice in pounds per square foot.

$C$  is the compressibility factor.

From equation (2), by arranging terms and collecting constants and conversion factors, the following equation results:

$$Q = 6.77 a' \sqrt{\frac{w r^2 (h_1 - h_2)}{r^2 - 1}} \quad \times C \quad (3)$$

where  $Q$  is the rate of flow in pounds per minute.

$a'$  is the area of the orifice in square inches.

$\alpha$  is the coefficient of discharge for the orifice.

$w$  is the density of the upstream air in pounds per cubic foot.

$r$  is the ratio of the pipe area to the orifice in inches of alcohol (Specific Gravity = 0.79).

$C$  is the compressibility factor.

6.77 is a constant obtained by taking all conversion factors and other constants and combining them into one.

Hodgson concluded that if the ratio of area was greater than 1.7 and the pressure of the downstream side of the orifice was not less than 98% of the total pressure the compressibility factor could be neglected and that a coefficient of discharge of 0.61 could be used with only small errors. Since the orifice was designed to operate within this limitation, then equation (3) may be modified to give the following relation:

$$Q = 2.168 \sqrt{w(h_1 - h_2)} \quad (4)$$

where  $Q$  is the rate of flow in pounds per minute.

$w$  is the air density in pounds per cubic foot.

$h_1 - h_2$  is the pressure drop across the orifice in inches of alcohol.

The only terms in equation (4) which have to be determined are the density of the upstream air and the pressure drop across the orifice. The density of the upstream air may be obtained by use of the barometer reading and the wet and dry bulb temperatures of the atmosphere from a psychrometric chart. The pressure drop can be read from a differential micromanometer connected in the intake line above and below the orifice.

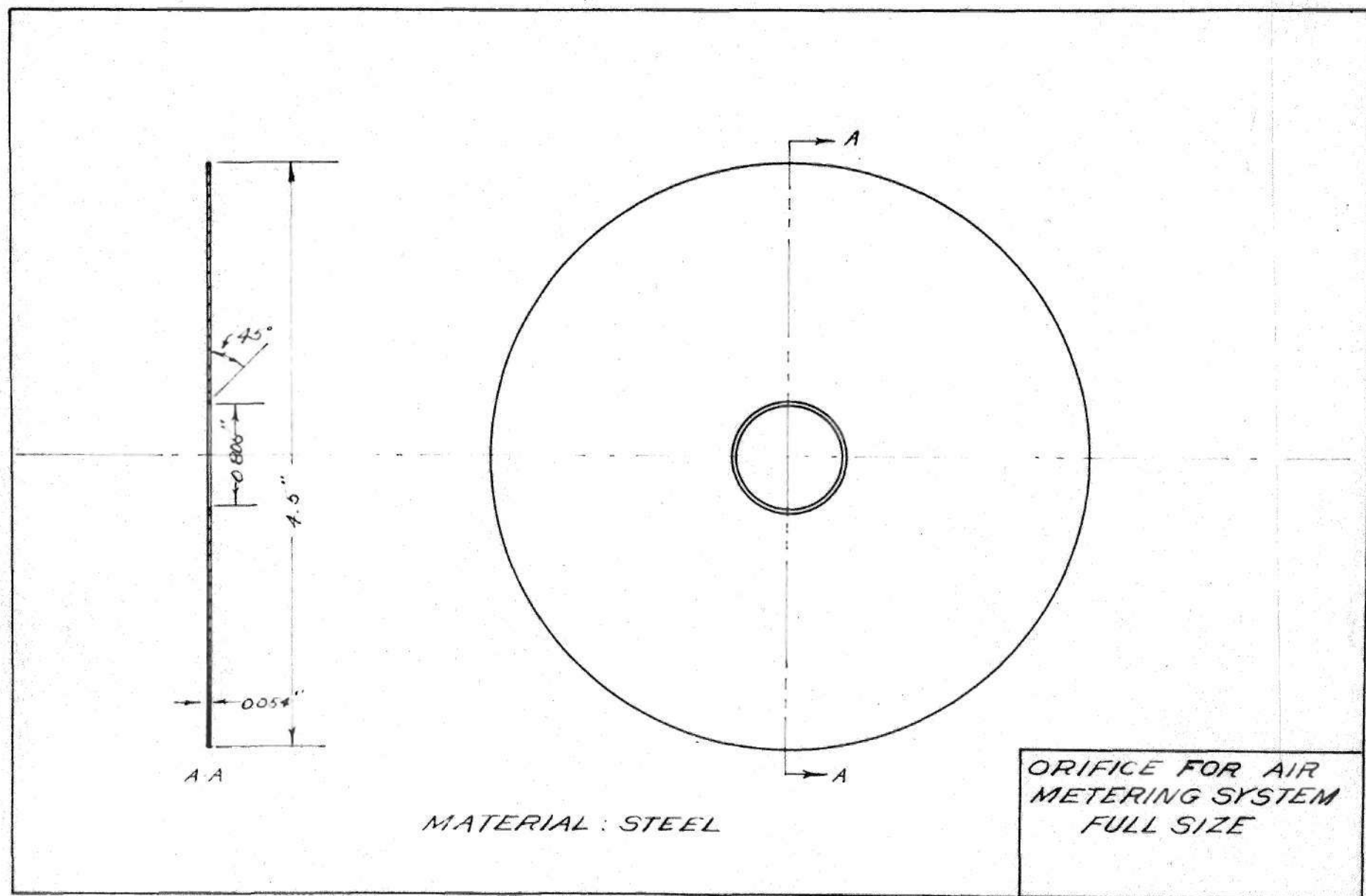
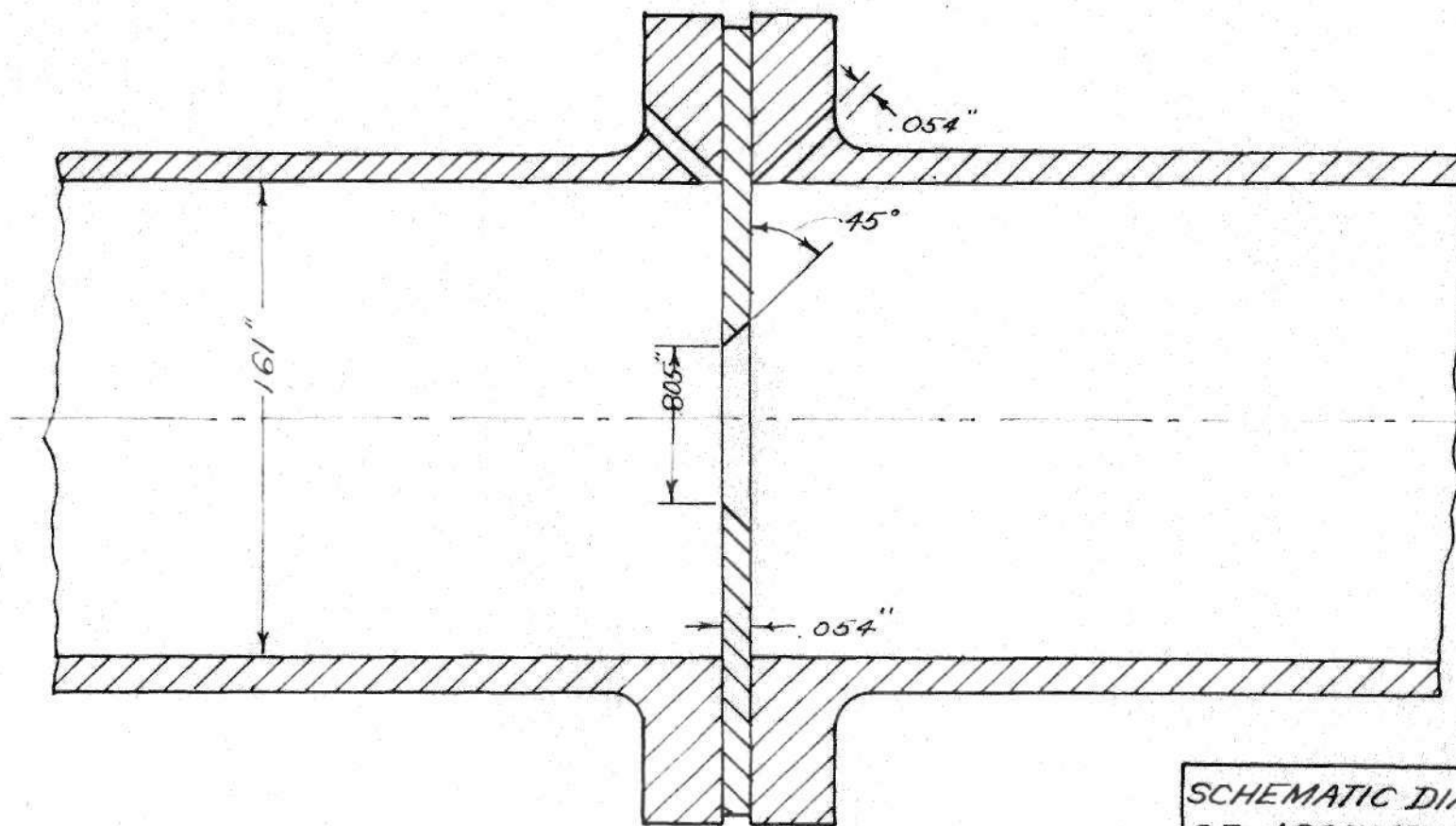


FIGURE 11





SCHEMATIC DIAGRAM  
OF ASSEMBLY OF  
ORIFICE PLATE IN  
PIPE LINE

FIGURE 12

## CALIBRATION OF THE PRESSURE INDICATING APPARATUS

The arrangement of equipment used to calibrate the pressure indicator is shown in Figure 13. The problem was to determine the amount of deflection caused on the oscilloscope image by a certain pressure on the diaphragm of the pressure indicator plug. To serve this purpose an apparatus was constructed which consisted of a hydraulic pump, a pressure gage and an adapter in which could be mounted the pressure indicator plug.

To calibrate the indicator apparatus the hydraulic pump was operated so as to apply a pressure on the indicator plug, the magnitude of this pressure being indicated by the pressure gage. This pressure on the indicator plug caused a corresponding deflection of the image on the oscilloscope screen. (See Figure 14).

The amount of this deflection was recorded on film in a Speed-Graphic camera by setting the shutter on time exposure. A metric scale mounted on the face of the oscilloscope served to give units which could be used to measure the magnitude of deflection. With the application of different pressure on the indicator plug and with the taking of a corresponding number of photographs, sufficient data was obtained to draw a calibration curve for the pressure indicating apparatus. This curve appears in Figure 14, and is valid only for the gain settings on the oscilloscope and oscillator detector which were used throughout the test runs.

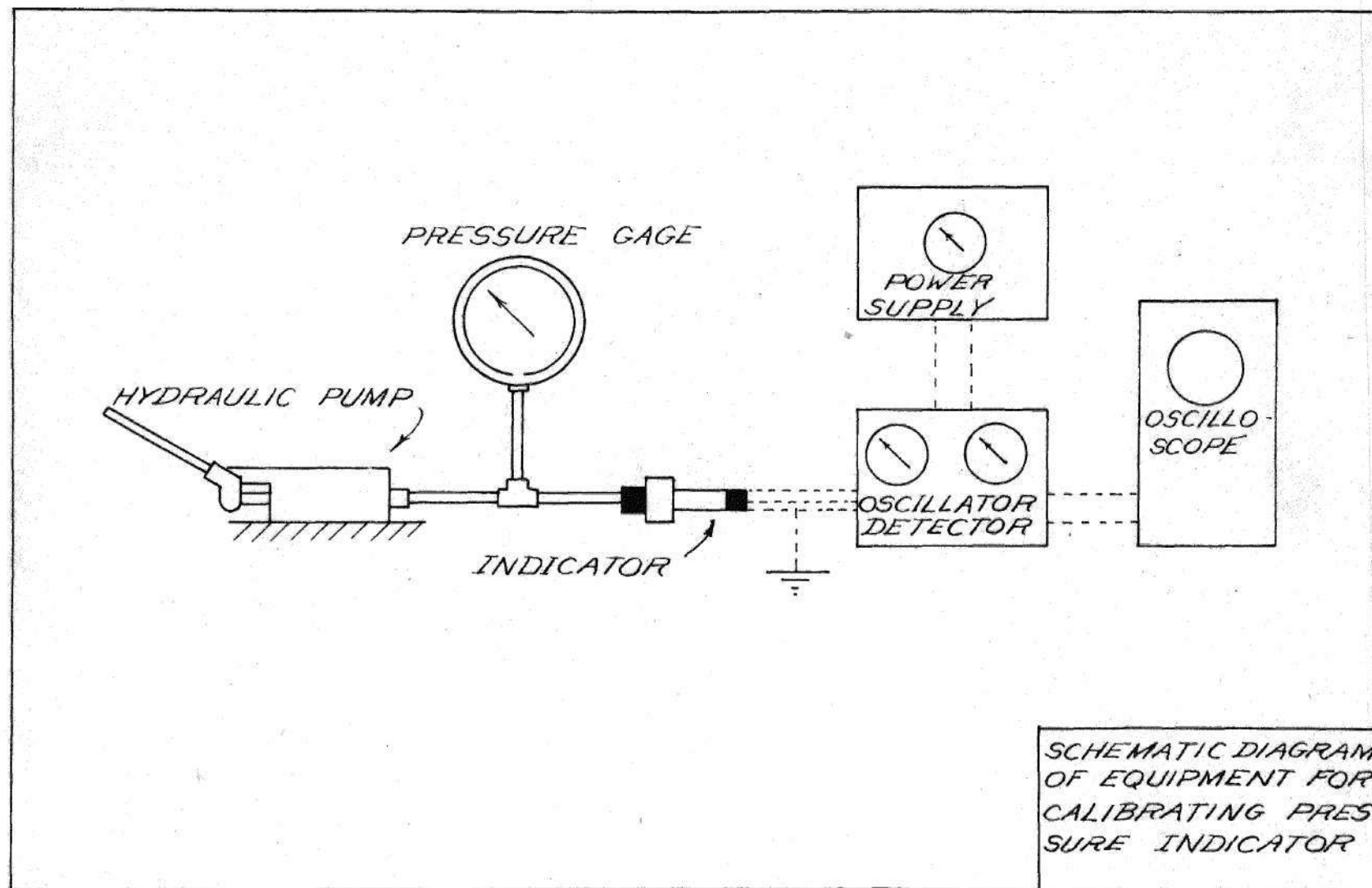
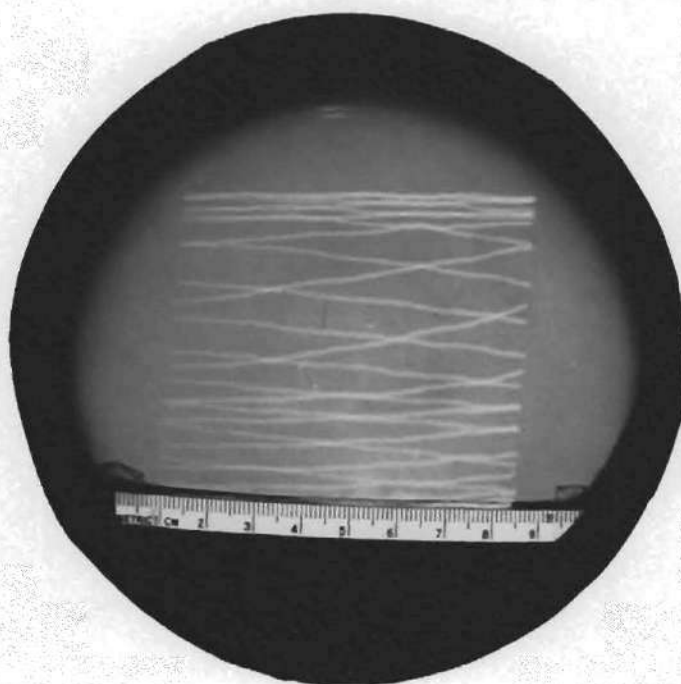
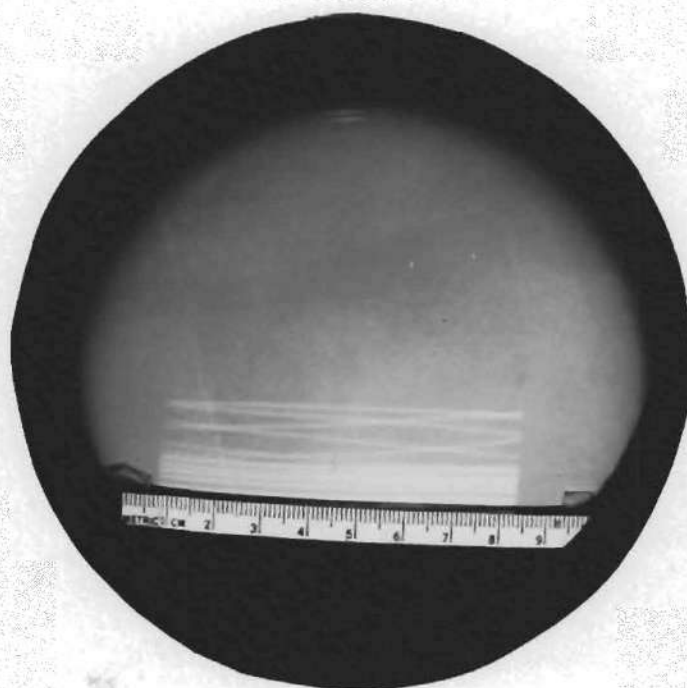


FIGURE 13

OSCILLOSCOPE PICTURES  
CALIBRATION OF PRESSURE INDICATING APPARATUS



DEFLECTION FOR PRESSURE OF 550 P.S.I.G.



DEFLECTION FOR PRESSURE OF 285 P.S.I.G.

FIGURE 14



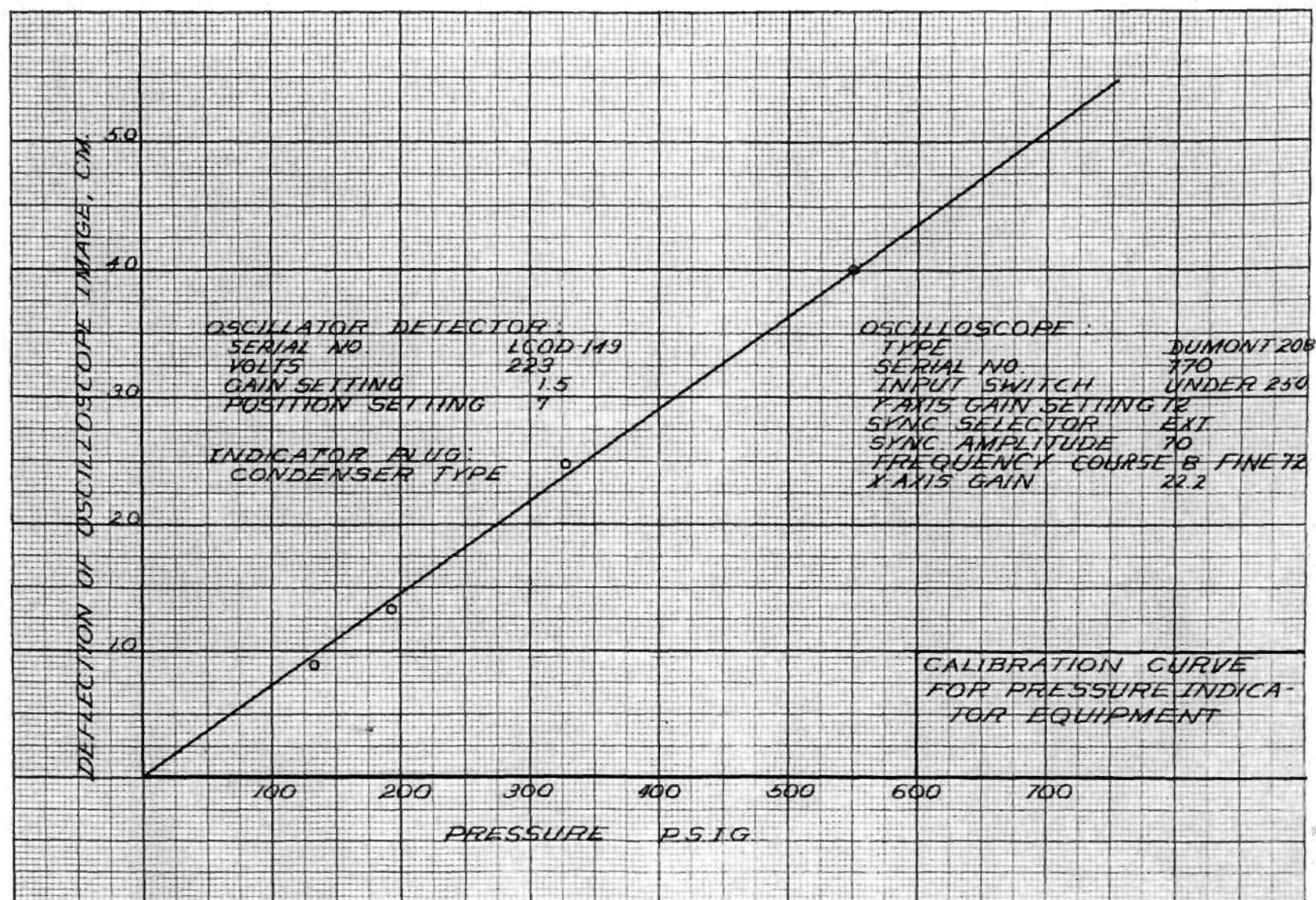


FIGURE 15

## CALIBRATION OF THERMOMETERS

## Thermometers:

The wet and dry bulb thermometers used in these tests were calibrated against a Bureau of Standards certified thermometer. The thermometers were calibrated for complete emergence.

Correction curves for the thermometers are shown in Figure 15.

Since the readings of the wet and dry bulb thermometers were the only temperatures which were used in the calculation of the flame density, it was considered unnecessary to calibrate any of the other thermometers used.



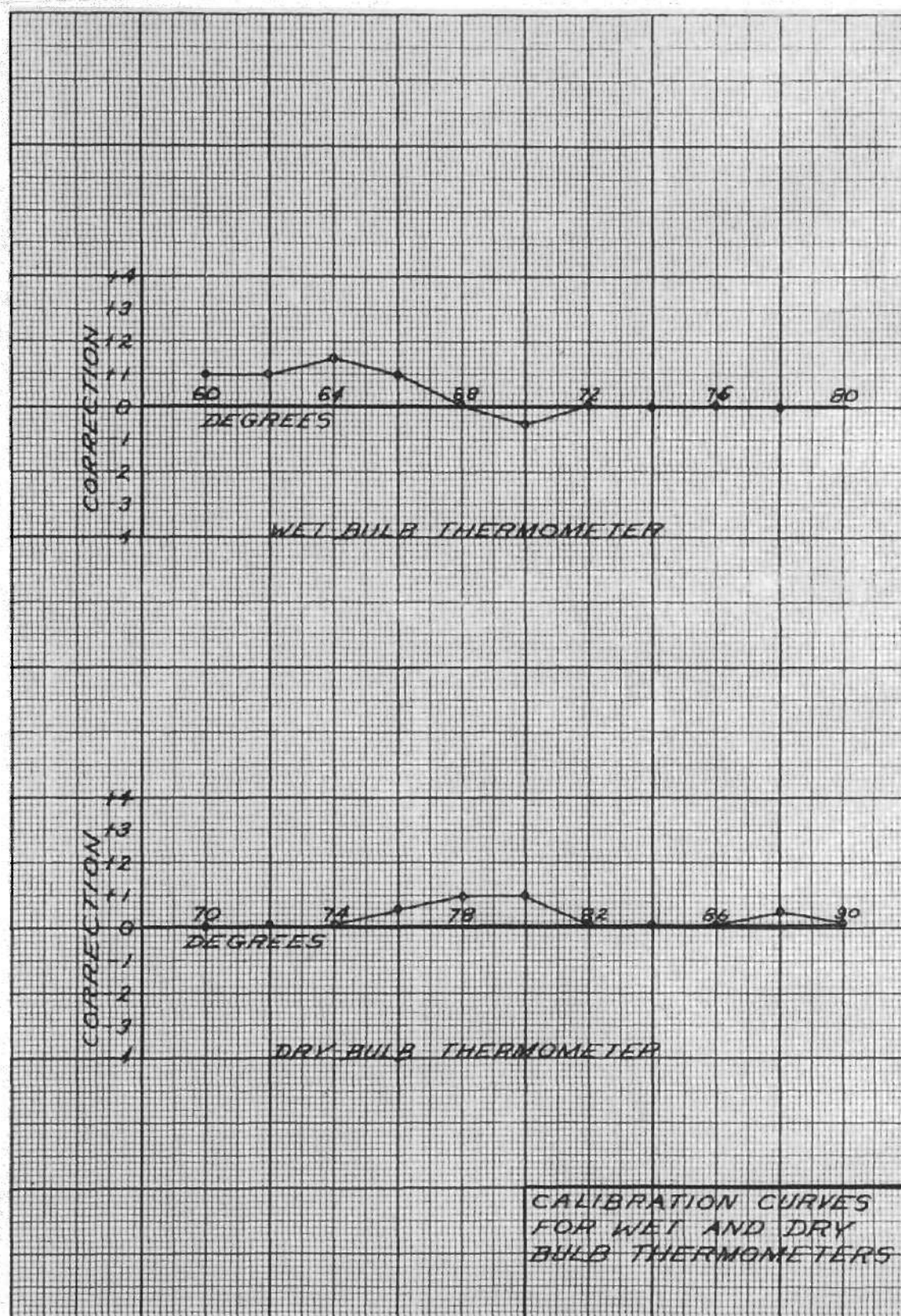


FIGURE 16

# APPENDIX III SAMPLE CALCULATIONS

A. Base length of image (using scale in photo) = 7.18 cm.

Since image brakes curve up in five parts, thus the  
length of curve =  $5 \times 7.18 = 35.9$  cm.

B. Position of spark:

Spark setting =  $20^\circ$  B.T.D.C.

Synchronizer setting =  $130^\circ$  B.T.D.C. = B.D.C.

Spark setting =  $180^\circ - 20^\circ = 160^\circ$  A.B.D.C.

Spark setting =  $\frac{160}{360} \times 35.9 = 15.95$  cm. (using scale in  
Photo)

C. For Run XII

$$\begin{aligned} \text{Compression ratio} &= \frac{5 \text{ } \cancel{\text{micrometer reading}}^4}{0.5 \text{ } \cancel{\text{micrometer reading}}} \\ &= \frac{5 \text{ } \cancel{0.434}}{0.5 \text{ } \cancel{0.434}} = 5.82 \end{aligned}$$

Letting

$V_A$  = Total volume in cylinder at B.D.C.

$V_B$  = Clearance volume at T.D.C.

$V_C$  = Displacement = 37.4 cu. in. =  $V_1 - V_2$

$R$  = Compression ratio =  $\frac{V_1}{V_2} = 5.82$

$$\text{Since } R = \frac{V_A}{V_B} = 5.82 \quad (1)$$

$$\text{then } V_A = (5.82) V_B \quad (2)$$

---

<sup>4</sup>C.F.R. Knock-Testing Manual, compiled by the Coordinating Fuel Research Committee of the Coordination Research Council, Inc., 30 Rockefeller Plaza, New York, New York



And since  $V_A - V_B = 37.4$  (3)

Substituting equation (2) with equation (3) gives:

$$5.82 V_B - V_B = 37.4$$

$$V_B(5.82 - 1) = 37.4$$

$$V_B = 7.76 \text{ cu. inches} \quad (4)$$

D. Quantity of air taken in per minute

$$Q = 2.168 V \sqrt{w(h_1 - h_2)} \quad (\text{see page 41}) \quad (5)$$

$Q$  = pounds of air flowing per minute

$w$  = air density in pounds per cubic foot.

$h_1 - h_2$  = pressure drop across orifice in inches of alcohol.

1. To determine  $W_1$  air density with wet bulb temperature = 78°F and dry bulb temperature = 90°F.

From Psychrometric chart at WB = 78 and DB = 90:

Specific volume of dry air = 14.22 cu. ft./lb.

Weight of water vapor in one pound of dry

air = 125 grains = 0.0173726 pounds.

Therefore, weight of 14.22 cu.ft. of air is  $1.000 + 0.01787$   
= 1.01787 pounds.

It follows that the density of the air =  $W = \frac{1.01787}{14.22}$   
= 0.0714 lb./cu. ft.

2. From data

$h_1 - h_2 = 0.5577$  inches of alcohol

Therefore  $Q = 2.168 V \sqrt{(0.0714)(0.5577)}$   
= 0.4326 pounds per minute

E. Quantity of fuel taken in per minute:

From data it required 22 minutes 10 seconds to burn 400 milliliters of fuel, and the density of the fuel = 0.715 grams per milliliter.

$F =$  pounds of fuel burned per minute. Since one gram equals  $\frac{1}{453.6}$  pounds

$$\text{then } F = \frac{(400)(0.715)}{(22.167)(453.6)}$$

$$F = 0.02855 \text{ pounds per minute}$$

F. Weight of mixture taken in per minute equals  $W_m$

$$W_m = Q / F = 0.4326 / 0.02855$$

$$W_m = 0.46115 \text{ pounds per minute}$$

G. Weight of fuel-air mixture taken in on intake stroke:

From data RPM = 901.3

$$\text{Number of intake strokes per minute} = \frac{901.3}{2} = 450.65$$

$$= W_{ms} \frac{0.46115}{450.65}$$

$$W_{ms} = 0.001022 \text{ pounds per intake stroke.}$$

H. Volume of chamber at beginning of combustion:

From data, position of piston at beginning of combustion =  $163.7^\circ$  A.B.D.C.

$$= 16.3^\circ \text{ B.T.D.C.}$$

Letting  $L_r$  = length of connect-

ing rod = 10.5 inches.

$L_c$  = Length of crank

$$= 2.25 \text{ inches}$$

$\phi$  = Rod angle from cylinder axis

At  $16.3^\circ$  B.T.D.C. to find  $m$ :

$$L_c \sin \Delta = L_r \sin \phi$$

$$\sin \phi = \frac{L_c}{L_r} \sin \Delta$$

$$= \frac{2.25}{10.5} \sin 16.3 = 0.0602$$

$$\phi = 3.45^\circ$$

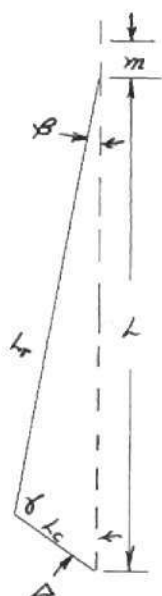
$$\gamma = 180 - 16.3 - 3.45 = 160.25$$

$$L = L_r \frac{\sin \gamma}{\sin \Delta} = \frac{\sin 160.25}{\sin 16.3}$$

$$L = 12.62 \text{ inches}$$

$$M = L_r \neq L_c - L = 10.5 \neq 2.25 - 12.62$$

$$= 0.13 \text{ inches}$$



Cylinder bore = 3.25 inches.

Volume in cylinder caused by displacement  $m$  is

$$V_m = 17 \frac{(3.25)^2}{4}$$

$$V_m = 1.079 \text{ cubic inches}$$

Therefore, the volume of combustion chamber at beginning of combustion is

$$V_c = \text{volume at T.D.C.} \neq V_m = V_2 \neq V_m$$

$$V_c = 7.76 \neq 1.079$$

$$V_c = 3.830 \text{ cubic inches}$$

I. Density of mixture at beginning of combustion =  $d_1$  in pounds per cubic foot.

$$d_1 = \frac{\text{weight of mixture}}{\text{volume}} = \frac{W_{ms}}{V_c} \times 1728$$

$$d_i = \frac{0.001022}{8.839} \times 1728$$

$$d_1 = 0.200 \text{ pounds per cubic foot.}$$

J. Determination of  $P_1 P_o P_i$ :

1.  $P_1$  = Pressure in chamber at beginning of combustion  
 = Pressure from calibration curve (using ordinate from oscilloscope picture)  $\div$  atmospheric pressure.

From oscilloscope picture (see Figures 7 and 8):

Ordinate at beginning of combustion = 2.135 cm.

From calibration curve, Figure 14, pressure for deflection of 2.135 cm. = 295 psi.

Borometric pressure = 29.005 in. Hg. = 14.23 psi.

Therefore  $P_1 = 295 \div 14.23 = 309.23$  psia.

2.  $P_o$  = Pressure in chamber at end of combustion:

Ordinate from picture = 7.43 cm.

Pressure for deflection = 1120 psi.

$P_o = 1120 \div 14.23 = 1135.23$  psia.

3.  $P_i$  = Instantaneous pressure (arbitrarily taken at 6°B.T.D.C.)

Ordinate from picture = 3.775 cm.

Pressure for deflection = 515 psi.

$P_i = 515 \div 14.23 = 529.23$  psia.

K. Calculation of Flame Density,  $d_1$ :

$$d_1 = d_1 y^{\frac{1}{n}} \left[ 1 - \frac{a - y}{a \div y (n-1)} \right]^{\frac{1}{n}}$$



$d_i$  = Gas density at beginning of combustion = 0.20

$$\gamma = \frac{P_i}{P_1} = \frac{529.23}{309.23} = 1.712$$

$$a = \frac{P_o}{P_1} = \frac{1134.23}{309.23} = 3.35$$

$$n = 1.35^5$$

$$d_i = 0.20 (1.712)^{\frac{1}{1.35}} \left[ 1 - \frac{3.35 - 1.712}{3.35 \cdot 1.712(1.35 - 1)} \right]$$

$$d_i = 0.174 \text{ pounds per cubic foot.}$$

---

<sup>5</sup> Leary, W. A. and Taylor, E. S., The Significance of the Time Concept in Engine Detonation, N.A.C.A. Wartime Report, W-32, 1942.